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QUANTUM UNIVERSE

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INSIDE

Record-Breaking Entanglement

Schrödinger's Cat, Reimagined

Superposition in the Lab

New Views of the Multiverse

When Will Quantum Computing Arrive?

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FROM THE EDITOR

On the Heels of a Light Beam

As a 16-year-old boy, Albert Einstein imagined chasing after a beam of light in the vacuum of space. He mused on that vision for years, turning it over in his mind, asking questions about the relation between himself and the beam. Those mental investigations eventually led him to his special theory of relativity. Such thought experiments, which Einstein referred to by the German term *gedankenexperiment,* continue to nourish the heart of physics today, especially in the field of quantum mechanics, which he helped to establish.

"In quantum mechanics, things don't happen," theoretical physicist Stephen L. Adler tells our reporter Tim Folger on page 36, referring to the probabilistic nature of quantum reality.

Philosophically, this may be true, but it hasn't stopped researchers from testing quantum concepts. Using lasers to excite electrons into emitting photons, a group at Delft University of Technology in the Netherlands ruled out the existence of "hidden variables," which Einstein believed were controlling so-called entangled particles—one of the main tenets of quantum theory (*page 18*). Without these mysterious forces, bizarre dynamics could indeed be at work in the quantum world, defying our notions of space and time. Physicist Lee Smolin argues (*page 4*) that the fabric of the cosmos is a vast collection of atomic interactions within an evolving network of relations where causality among events is complex and irrespective of distance.

Despite the theoretical mysteries of quantum theory, its real-world applications are growing. Researchers are cooling atomic systems to near absolute zero for use as quantum simulators to study applications in superconductors and superfluids (*page 66*). Others are using tabletop experiments to monitor the gravitational fields around entangled objects—minuscule gold or diamond spheres, for example—looking for signs that gravity itself is "quantized" into discrete bits (*page 52*). At a larger scale, tools such as the Event Horizon Telescope, which recently took the first picture of a black hole, and gravitational-wave detectors could help resolve long-standing, vexing contradictions between quantum mechanics and general relativity (*page 70*).

These quantum insights are fueling tremendous innovation. A team of researchers in China successfully tested superposition over a distance of 1,200 kilometers, paving the way for an unhackable quantum-communications network (*page 102*). Computer scientists are using quantum algorithms to enhance traditional systems, ratcheting up progress toward the heralded quantum computing era (*page 86*). Such applications are still immature, as Elizabeth Gibney reports (*page 106*), yet it's not stopping investors from pouring money into quantum start-ups.

Science historians have argued about whether Einstein accepted the elements of quantum theory that conflicted with his own theories (*page 12*). Who knows whether he could have imagined the applications his ideas engendered. In any case, the thought experiment continues.

Andrea Gawrylewski
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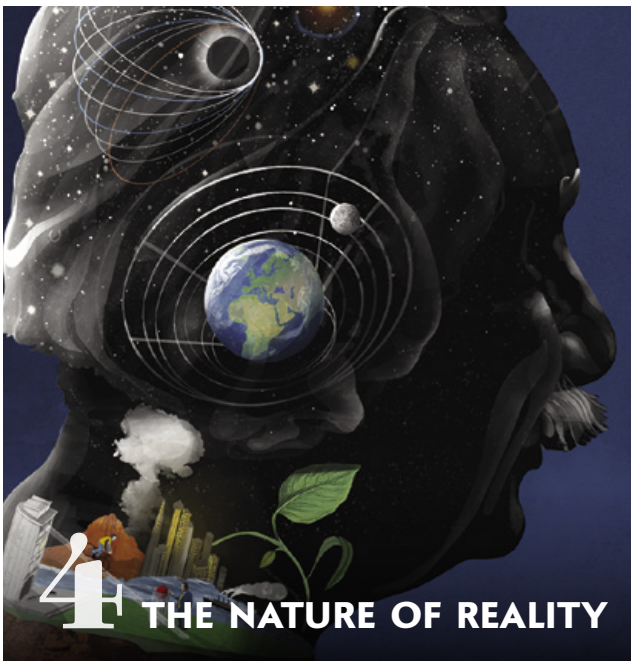

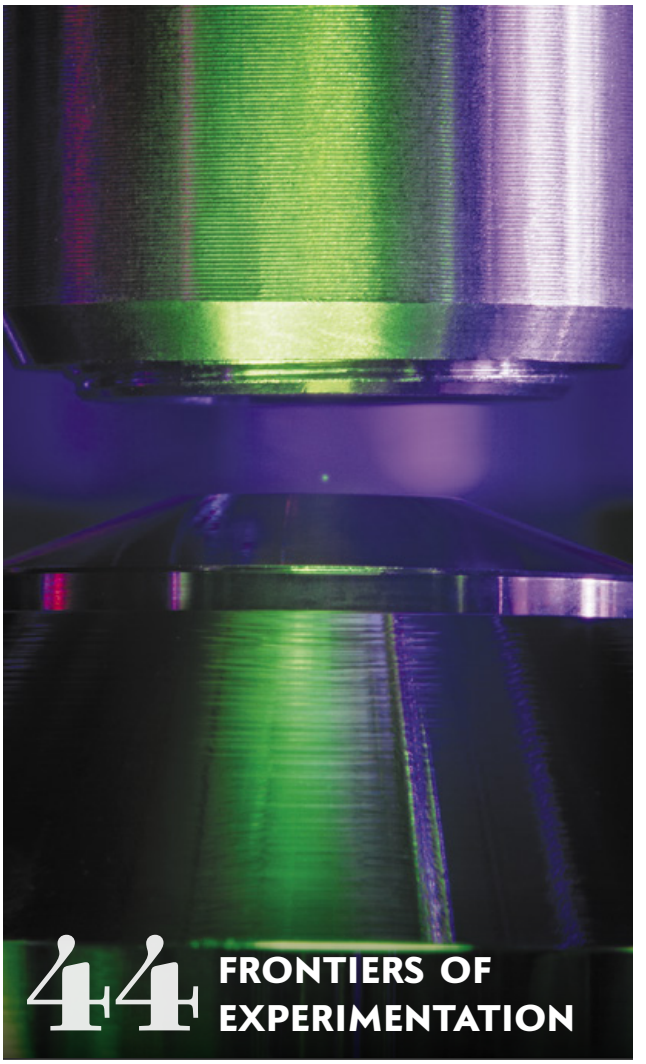

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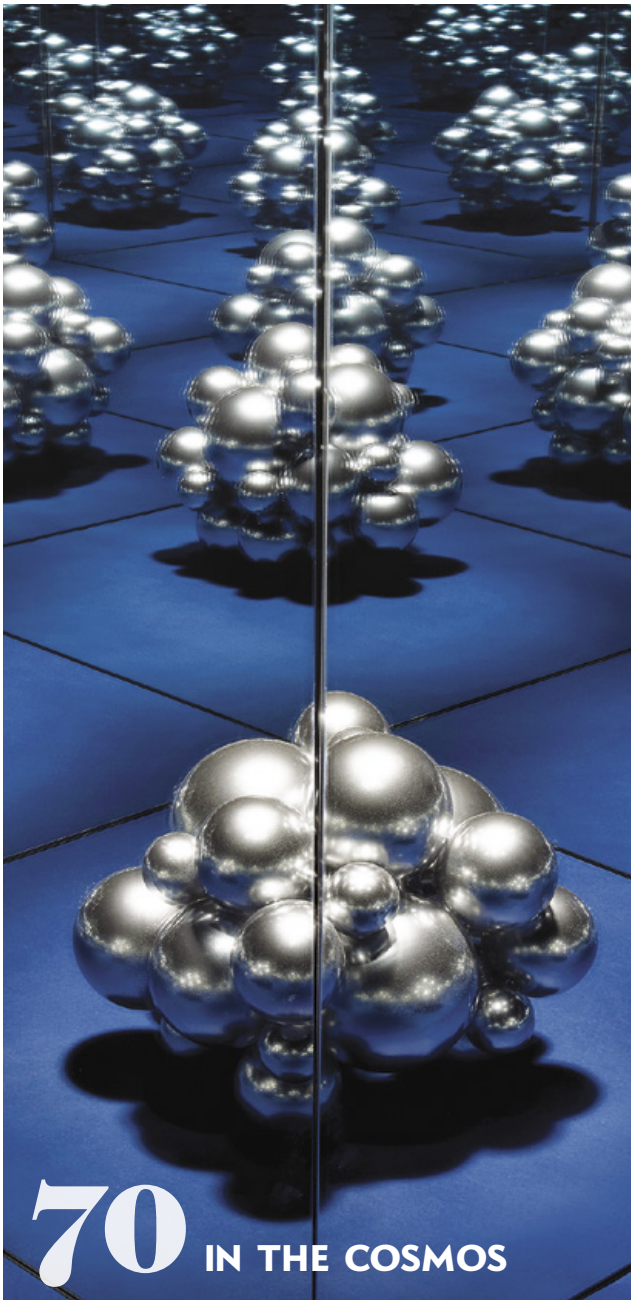

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THE FINAL ILLUSION

The intuitive idea that objects influence each other because they are in physical proximity is soon to become another of those beliefs that turn out to be wrong when we look deeper

By Lee Smolin

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MANY OF THE GREAT ADVANCES IN SCIENCE ARE MARKED BY the discovery that an aspect of nature we thought was fundamental is actually an illusion, the result of the coarseness of our sensory perceptions. Thus, air and water appear to us to be continuous fluids, but we discover on deeper experiment that they are made of atoms. Earth appears to us motionless, but a deeper understanding teaches us that it moves relative to the sun and the galaxy.

One persistent illusion is that physical objects only interact with other objects they are close to. This is called the principle of locality. We can express this idea more precisely by the law that the strength of forces between any two objects falls off quickly—at least by some power of the distance between them. This can be explained by positing that the bodies do not interact directly but only through the mediation of a field, such as an electromagnetic field, which propagates from one body to the other. Fields spread out as they propagate, with the field lines covering a constantly greater area—providing a natural explanation for the laws that say the forces between charges and masses fall off like the square of the distance between them.

Locality is an aspect of an even more compelling illusion: that we exist within an absolute space, with respect to which we mark our positions as we move "through" it. Thus, Isaac Newton opined that motion is ultimately defined as change of position with respect to absolute space. If this seems obscure—because no measurement can establish a relation of a physical object to this imagined absolute space—Newton assured us that absolute space is seen by God, making your location relative to it an aspect of the divinity of the world. We humans must make do with relative positions and motions—which are defined relative to physical objects we can see.

Gottfried Wilhelm Leibniz broke the mystification by declaring that all that exists is relative positions and motions. He proposed as a matter of principle that any acceptable science of motion must be formulated in terms of relative motions alone. And this, after two centuries of waiting, is what Albert Einstein delivered to us in his general theory of relativity. In this glorious construction, space is subsumed into spacetime, which is explicable as a dynamically evolving network of relations.

And what defines those relations? Nothing but causality. The elements of spacetime are events—the ultimate expression of locality—and each of these is caused by events in their past. Each event will also become a cause of events in the future. Most of the information in the geometry of spacetime is actually a coding of the relations of causality that relate the events.

Thus, we see that the idea that physical forces must act locally is a consequence of a deeper principle, which is that physical effects have causal processes. And the basic principles of relativity theory insist that causes can only propagate through space at a finite speed, which cannot exceed the speed of light. We call this the principle of relativistic causality.

This principle would seem to be so natural that it must be true. But not so fast. Of all the strange aspects of quantum physics so far discovered, the strangest of all has to be the shocking discovery that the principle of relativistic causality is violated by quantum phenomena. Roughly speaking, if two particles interact and then separate, flying far apart from each other, they nonetheless may continue to share properties of a strange kind, that may be ascribed to the pair, without each of the individuals having themselves any definite properties. We say the two particles are "entangled."

When two particles are in such an entangled state, an experimenter can, it turns out, affect the properties of one of the particles, directly and immediately, by choosing to measure some particular corresponding property of the other. It matters not at all that it would require a signal much faster than light to directly effect such an influence.

This has been shown in many experiments carried out since the 1970s, which test a notion of locality formulated by John Bell in 1964—and all the results show that entangled pairs violate that concept of locality.

In its present form, quantum mechanics only predicts statistical averages for the outcomes of many kinds of experiments, including these. Consequently, it is not possible to use the nonlocality present in entangled pairs to send a signal faster than light. But many physicists, in an ambition going back to Einstein, Louis de Broglie, Erwin Schrödinger and the other inventors of quantum mechanics, aspire to discover an improved version of quantum theory.

This would go deeper and replace the present statistical theory with a more complete theory, which would provide a complete and exact description of what goes on in every individual quantum process. For such a theory to work, it would have to be based on influences traveling arbitrarily faster than light, thus destroying the principle of relativistic causality as well as our intuitive notions of local influence.

Is such a more complete understanding of quantum physics possible? And how are we to search for it? I believe it is not only possible but an inevitable next step in the progress of physics. I believe that the completion of quantum mechanics will be a major part of the resolution of another deep problem—that of

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unifying our understandings of gravity, spacetime and the quantum, to produce a quantum theory of gravity.

The reason is that there is good evidence that the quantum theory of gravity will itself engender big violations of locality. And as Fotini Markopoulou, also then at the Perimeter Institute, and I first proposed in 2003, the violations of locality forced on us by quantum gravity are precisely what are needed to explain the nonlocality brought on by quantum entanglement.

If we are to have a complete physics, we must unify the geometrical picture of spacetime given by general relativity with quantum physics. There is some theoretical evidence that this project of making a quantum theory of gravity will require space and spacetime to become discrete and built out of finite atoms of geometry.

In the same sense that a liquid is just a description of the collective motions of myriads of atoms, space and spacetime will turn out to be just a way of talking about the collective properties of the large number of atomic events. Their constant coming in and out of being, causing the next ones as they recede into the past, make up the continual construction of the world—also known to us as the flow of time.

The aim of a quantum theory of gravity is then first to hypothesize the laws that govern the elementary events, by which they continually come into being and then recede into the past. Then we must show how a large-scale picture emerges, in which these discrete events become subsumed in an emergent description of a smooth and continuous spacetime—as described by Einstein's 1915 general theory of relativity.

Initially there is no space—just a network of individual elementary events, together with the relations expressing which of these were the direct causes of which other events. The notion of the flow of events collectively giving rise to a smooth description in terms of the geometry of a spacetime must emerge—and the most important aspect of this is locality. The notion of distance must emerge, and in such a way that those events that are close to each other are, on average, correspondingly more likely to have influenced each other. Getting this right is the holy grail of quantum gravity theorists.

Notice that if this is right, there are two notions of locality: a fundamental locality, which is based on the actual facts of which fundamental events were causes of which, and an approximate, collective, emergent notion of which events are near to each other in space and spacetime. The familiar macroscopic notion of distance is then based on a collective averaging of all the myriad of fundamental causal processes. To get a sense of how much is involved in this average, we expect that during each second there are around 10^{120} elementary events happening within each cubic centimeter of space.

Indeed, one way to approach quantum gravity is to aim to derive the Einstein equations, which are the laws general relativity applies to spacetime, from the laws of thermodynamics, applied to myriads of elementary events. This strategy was introduced in 1995 by Ted Jacobson of the University of Maryland, College Park, in one of the few papers admired by quantum gravity theorists of all stripes.

But here we get a surprise and, quite possibly, an opportunity. For the collective, large-scale notion of nearness is only meant to correspond to the fundamental notion of causality when averaged over vast numbers of events. This gives the individual fundamental events and their causal relations a great deal of freedom to depart from the averages.

For example, let us pick just two elementary events, one in the cup of coffee you are now drinking and the other in a cup of whatever it is they drink on one of the planets of Proxima Centauri. These events may be separated by four light-years—but nothing prevents one from being an elementary cause of the other.

We can choose these two events so that they are nearly simultaneous as we (or the Proximas) measure time. Thus, it violates the principles of Einstein's theories of relativity to have one of these events be the cause of the other. But there need not be a contradiction if we regard the laws of relativity as emergent regularities to govern the collective large-scale average. This is just how we regard the laws of thermodynamics as arising from averages over large collections of atoms, whose individuals follow different laws.

When a law emerges from a statistical averaging, there are always relatively rare events, in which individual atoms violate the rule that holds on average. We call these fluctuations. A good example is the tendency of collections of atoms, when cooled, to form regular crystal patterns. But from time to time an atom ends up in the wrong place, disrupting the beautiful symmetry of the crystal arrangement. We say the pattern has been disordered.

I can then summarize the story I've been telling by saying that when locality, and space itself, emerges from averaging over fundamental processes involving a myriad of individual events, it is inevitable that locality will be disordered. Mostly, influences will be local because most of the time, causally related events will end up close to each other in the emergent rough description we call space. But there will be many pairs of events that are causally related, that will end up far from each other—thus disordering space and locality.

Could this disordering of locality serve to explain the quantum nonlocality inherent in entangled particles? I believe the answer is yes. Indeed, we have shown this to be the case in two different models of fundamental completions of quantum mechanics.

The details are unimportant, especially at this early stage. But the takeaway lesson is that the intuitive idea that objects influence each other because they are close in space is soon to become another of those easy beliefs that turn out to be wrong when we look deeper. The smoothness of space is soon to become an illusion that hides a tiny and complex world of causal interactions, which do not live in space—but which rather define and create space as they create the future from the present. SA

Lee Smolin is a senior and founding faculty member at the Perimeter Institute for Theoretical Physics in Waterloo, Ontario, and adjunct professor of physics at the University of Waterloo. In addition to his work on quantum gravity, he is interested in elementary particle physics, cosmology and the foundation of quantum theory. His latest book is *Einstein's Unfinished Revolution,* published in 2019 by Penguin.

MORE TO EXPLORE

Thermodynamics of Spacetime: The Einstein Equation of State. Ted Jacobson. Article 9504004; revised June 6, 1995. Preprint available at **arXiv.org**

Quantum Theory from Quantum Gravity. Fotini Markopoulou and Lee Smolin. Article 0311059; revised June 14, 2004. Preprint available on **arXiv.org**

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HEAD TRIP

Einstein's thought experiments left a long and somewhat mixed legacy of their own

By Sabine Hossenfelder

GEDANKENEXPERIMENT, GERMAN FOR "THOUGHT EXPERIMENT," WAS Albert Einstein's famous name for the imaginings that led to his greatest breakthroughs in physics. He traced his realization of light's finite speed—the core idea of special relativity—to his teenage daydreams about riding beams of light. General relativity, his monumental theory of gravitation, has its origins in his musings about riding up and down in an elevator. In both cases, Einstein crafted new theories about the natural world by using his mind's eye to push beyond the limitations of laboratory measurements.

Einstein was neither the first nor the last theorist to do this, but his remarkable achievements were pivotal in establishing the *gedankenexperiment* as a cornerstone of modern theoretical physics. Today physicists regularly use thought experiments to formulate new theories and to seek out inconsistencies or novel effects within existing ones.

But the modern embrace of thought experiments raises some uncomfortable questions. In the search for a grand unified theory that would wed the small-scale world of quantum mechanics with Einstein's relativistic description of the universe at large, the most popular current ideas are bereft of observational support from actual experiments. Can thought alone sustain them? How far can we trust logical deduction? Where is the line between scientific intuition and fantasy? Einstein's legacy offers no certain answers: On one hand, his reliance on the power of thought was a spectacular success. On the other, many of his best known thought experiments were based on data from real experimentation, such as the classic Michelson-Morley experiment that first measured the constancy of the speed of light. Moreover, Einstein's fixation on that which can be measured at times blinded him to deeper layers of reality—although even his mistakes in thought experiments contributed to later breakthroughs.

Here we will walk through some of Einstein's most iconic thought experiments, highlighting how they succeeded, where they failed and how they remain vital to questions now at the frontiers of theoretical physics.

Illustration by Sam Falconer

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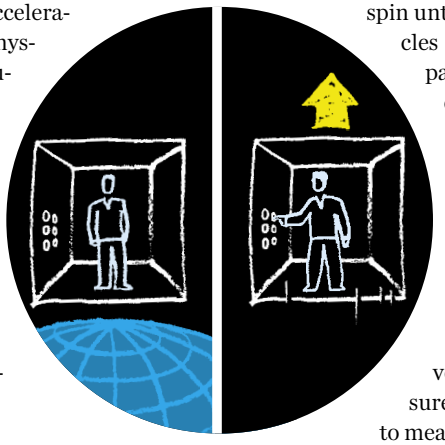
THE WINDOWLESS ELEVATOR

IN HIS THOUGHT EXPERIMENTS, Einstein's genius was in realizing which aspects of experience were essential and which could be discarded. Consider his most famous one: the elevator thought experiment, which he began devising in 1907. Einstein argued that inside a windowless elevator, a person cannot tell whether the elevator is at rest in a gravitational field or is instead being hauled up with constant acceleration. He then conjectured that the laws of physics themselves must be identical in both situations. According to this "principle of equivalence," locally (in the elevator), the effects of gravitation are the same as that of acceleration in the absence of gravity. Converted into mathematical equations, this principle became the basis for general relativity. In other words, the elevator thought experiment motivated Einstein to make the daring intellectual leap that ultimately led to his greatest achievement, his geometric description of gravity.



SPOOKY ACTION

LATER IN HIS CAREER, Einstein fought hard against the tenets of quantum mechanics, particularly the uncertainty principle, which dictates that the more you know about one aspect of a fundamental particle, such as its position, the less you can know about another related aspect of that particle, such as its momentum—and vice versa. Einstein thought that the uncertainty principle was a sign that quantum theory was deeply flawed.

During a years-long exchange with Danish quantum theorist Niels Bohr, Einstein conceived of a series of thought experiments meant to demonstrate that it is possible to violate the uncertainty principle, but Bohr dissected every one of them. This exchange bolstered Bohr's conviction that quantum uncertainty was a fundamental aspect of nature. If not even the great Einstein could devise a way to precisely measure both the position and the momentum of a particle, then certainly there must be something to the uncertainty principle!

In 1935, along with his colleagues Boris Podolsky and Nathan Rosen, Einstein published what was meant to be his most potent critique of the uncertainty principle. Perhaps because Podolsky, not Einstein, drafted the actual text of the paper, this Einstein-Podolsky-Rosen (EPR) thought experiment was presented not as an easy-to-imagine scenario of boxes, clocks and light beams but as an abstract series of equations describing interactions between two generalized quantum systems.

The simplest version of the EPR experiment studies the paradoxical behavior of "entangled" particles—pairs of particles that share a common quantum state. It unfolds as follows: imagine an unstable particle with a spin of zero decaying into two daughter particles, which speed off in opposite directions. (Spin is a measure of a particle's angular momentum, but counterintuitively, it has little to do with a particle's rate of rotation.) Conservation laws dictate that the spins of those two daughter particles must add up to zero; one particle, then, could possess a spin value of "up," and the other could have a spin value of "down." The laws of quantum mechanics dictate that in the absence of measurement, neither of the particles possesses a definite spin until one of the two speeding entangled particles is measured. Once a measurement of one particle is made, the state of the other changes *instantaneously,* even if the particles are separated by vast distances!

Einstein believed this "spooky action at a distance" was nonsense. His own special theory of relativity held that nothing could travel faster than light, so there was no way for two particles to communicate with each other instantaneously from opposite sides of the universe. He suggested instead that the measurement outcomes must be determined prior to measurement by "hidden variables" that quantum mechanics failed to account for. Decades of discussion followed until 1964, when physicist John Stewart Bell developed a theorem quantifying exactly how the information shared between entangled particles differs from the information that Einstein postulated would be shared through hidden variables.

Since the 1970s lab experiments with entangled quantum systems have repeatedly confirmed that Einstein was wrong, that quantum particles indeed share mutual information that cannot be accounted for by hidden variables. Spooky action at a distance is real, but experiments have demonstrated that it cannot be used to transmit information faster than light, making it perfectly consistent with Einstein's special relativity. This counterintuitive truth remains one of the most mysterious conundrums in all of physics, and it was Einstein's stubborn, mistaken opposition that proved crucial to confirming it.

ALICE AND BOB

TODAY SOME OF THE MOST SIGNIFICANT thought experiments in physics explore how to reconcile Einstein's clockwork, relativistic universe with the fuzzy uncertainties inherent to quantum particles.

Consider, for instance, the widely discussed black hole information paradox. If you combine general relativity and quantum field theory, then you find that black holes evaporate, slowly radiating away their mass because of quantum effects. You also find that this process is not reversible: regardless of what formed the black hole, the evaporating black hole always produces the same featureless bath of radiation from which no information about its contents can be retrieved. But such a process is prohibited in quantum theory, which states that any occurrence can, in

IN BRIEF

One of Einstein's enduring contributions to physics was his use of *gedanken-experiments,* or thought experiments.

His intuition about falling elevators, for example, led to his greatest achievement, the general theory of relativity.

Today some of the most important questions in theoretical physics involve thought experiments about black holes.

Yet there is a problem: these thought experiments may be so far removed from empirical data as to be untestable.

Illustrations by Nigel Holmes

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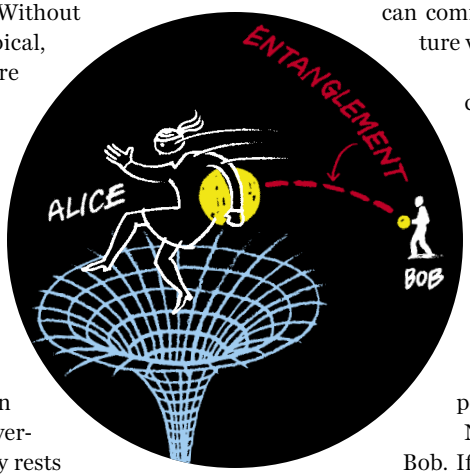
principle, be reversed in time. For instance, according to the laws of quantum mechanics, the leftovers of a burned book still contain all the information necessary to reassemble that book even though this information is not easily accessible. Not so for evaporating black holes. And so we arrive at a paradox, a logical inconsistency. A union of quantum mechanics and general relativity tells us that black holes must evaporate, but we conclude that the result is incompatible with quantum mechanics. We must be making some mistake—but where?

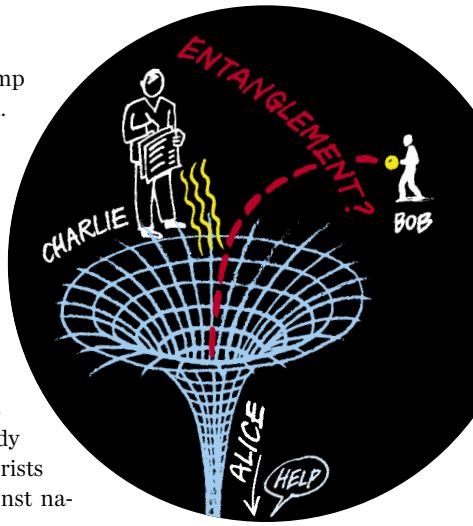
The thought experiments created to explore this paradox typically ask us to imagine a pair of observers, Bob and Alice, who share a pair of entangled particles—those spooky entities from the EPR experiment. Alice jumps into the black hole, carrying her particle with her, whereas Bob stays outside and far away with his. Without Alice, Bob's particle is just typical, with a spin that might measure up or down—the information that it once shared with its entangled partner is lost, along with Alice.



Bob and Alice play a central role in one of the most popular proposed solutions to the paradox, called black hole complementarity. Proposed in 1993 by Leonard Susskind, Lárus Thorlacius and John Uglum, all then at Stanford University, black hole complementarity rests on Einstein's golden rule for a *gedanken-experiment:* a strict focus on that which can be measured. Susskind and his colleagues postulated that the information falling in with Alice must come out later with the evaporating black hole's radiation. This scenario would usually create another inconsistency because quantum mechanics allows only pair-wise entanglement with one partner at a time, a property called monogamy of entanglement. That is, if Bob's particle is entangled with Alice's, it cannot be entangled with anything else. But black hole complementarity requires that Bob's particle be entangled with Alice's *and* with the radiation the black hole later emits even though this violates monogamy. At first sight, then, black hole complementarity seems to exchange one inconsistency with another.

But like a perfect crime, if no one actually *witnesses* this inconsistency, perhaps it can subvert nature's otherwise strict laws. Black hole complementarity relies on the argument that it is physically impossible for any observer to see Alice and Bob's entangled particles breaking the rules.

To envision how this perfect quantum-mechanical crime could unfold, imagine a third observer, Charlie, hovering near the black hole, keeping an eye on Alice and Bob. He watches as Bob stays outside and as Alice falls in, measuring the black hole's emitted radiation all the while. In theory, information encoded in that radiation could tip off Charlie that Bob and Alice had violated the monogamy of their entanglement. To know for certain, however, Charlie would have to compare his observations not only with Bob's measurement but also with Alice's—*inside* the black hole. So he must hover at the horizon, measure the emitted radiation, then jump in to tell Alice what he has found. Amazingly enough, Susskind and Thorlacius showed that no matter how hard Charlie tries, it is impossible for him to enter the black hole and compare his information with Alice's before they are both torn apart by tidal forces. Their grisly fate suggests no violations of quantum mechanics can ever be measured by anybody around a black hole, and so theorists can commit this crime against nature with impunity.



Suffice it to say, not all theorists are convinced that this argument is valid. One criticism of black hole complementarity is that it might violate Einstein's equivalence principle—the one that grew out of his elevator thought experiment. Einstein's general relativity predicts that just as the elevator's passenger cannot distinguish between gravity and acceleration, an observer crossing a black hole's horizon should not notice anything unusual; there is no way an observer can tell that he or she has slipped past the point of no return.

Now let us return to the entanglement of Alice and Bob. If the radiation that Bob sees from far outside the hole contains all the information that we thought vanished with Alice behind the horizon, then this radiation must have been emitted with an extremely high energy; otherwise, it would not have escaped the strong gravitational pull near the horizon. This energy is high enough to vaporize any infalling observer before he or she slips past the black hole's horizon. In other words, black hole complementarity implies that black holes have a "firewall" just outside the horizon—and yet the firewall directly contradicts the predictions of Einstein's equivalence principle.

At this point, we have ventured deep into the realm of theory. Indeed, we might never know the solutions to these puzzles. But because those solutions could lead to an understanding of the quantum nature of space and time, these puzzles are, for better or worse, some of the most vibrant areas of research in theoretical physics. And it all goes back to Einstein's musings about falling elevators. SA

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MORE TO EXPLORE

Einstein's Dice and Schrödinger's Cat: How Two Great Minds Battled Quantum Randomness to Create a Unified Theory of Physics. Paul Halpern. Basic Books, 2015.

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IS THE COSMOS RANDOM?

Einstein's assertion that God does not play dice with the universe has been misinterpreted

By George Musser

Few of Albert Einstein's sayings have been as widely quoted as his remark that God does not play dice with the universe. People have naturally taken his quip as proof that he was dogmatically opposed to quantum mechanics, which views randomness as a built-in feature of the physical world. When a radioactive nucleus decays, it does so spontaneously; no rule will tell you when or why. When a particle of light strikes a half-silvered mirror, it either reflects off it or passes through; the outcome is open until the moment it occurs. You do not need to visit a laboratory to see these processes: lots of Web sites display streams of random digits generated by Geiger counters or quantum optics. Being unpredictable even in principle, such numbers are ideal for cryptography, statistics and online poker.

Einstein, so the standard tale goes, refused to accept that some things are indeterministic—they just happen, and there is not a darned thing anyone can do to figure out why. Almost alone among his peers, he clung to the clockwork universe of classical physics, ticking mechanistically, each moment dictating the next. The dice-playing line became emblematic of the B side of his life: the tragedy of a revolutionary turned reactionary who upended physics with relativity theory but was, as Niels Bohr put it, "out to lunch" on quantum theory.

Over the years, though, many historians, philosophers and physicists have challenged this story line. Diving into what Einstein actually said, they have found that his thinking about indeterminism was far more radical and nuanced than is commonly portrayed. "It becomes a kind of a mission to get the story right," says Don A. Howard, a historian at the University of Notre Dame. "It's amazing when you dig into the archives and

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see the disparity from the common narrative." As he and others have shown, Einstein accepted that quantum mechanics was indeterministic—as well he might, because he was the one who had *discovered* its indeterminism. What he did not accept was that this indeterminism was fundamental to nature. It gave every indication of arising from a deeper level of reality that the theory was failing to capture. His critique was not mystical but focused on specific scientific problems that remain unsolved to this day.

The question of whether the universe is a clockwork or a craps table strikes at the heart of what we suppose physics to be: a search for simple rules that underlie the wondrous diversity of nature. If some things happen for no reason, they mark the limits of rational inquiry. "Fundamental indeterminism would mean an end to science," worries Andrew S. Friedman, a cosmologist at the Massachusetts Institute of Technology. And yet philosophers throughout history have supposed that indeterminism is a prerequisite for human free will. Either we are all gears in the clockwork, so that everything we do is preordained, or we are the agents of our own destiny, in which case the universe must not be deterministic after all. This dichotomy has had very real consequences for how society holds people responsible for their actions. Assumptions about free will suffuse our legal system; to be culpable, an offender must have acted with intent. The courts continually wrestle with whether people are innocent by reason of insanity, adolescent impulsiveness or rotten social background.

Whenever people talk about a dichotomy, though, they usually aim to expose it as false. Indeed, many philosophers think it is meaningless to say whether the universe is deterministic or indeterministic. It can be either, depending on how big or complex your object of study is: particles, atoms, molecules, cells, organisms, minds, communities. "The distinction between determinism and indeterminism is a level-specific distinction," says Christian List, a philosopher at the London School of Economics and Political Science. "If you have determinism at one particular level, it is fully compatible with indeterminism, both at higher levels and at lower levels." The atoms in our brain can behave in a completely deterministic way while still giving us freedom of action because atoms and agency operate on different levels. Likewise, Einstein sought a deterministic subquantum level without denying that the quantum level was probabilistic.

WHAT EINSTEIN OBJECTED TO

HOW EINSTEIN EVER GOT TAGGED as antiquantum is almost as big a mystery as quantum mechanics itself. The very notion of quanta—of discrete units of energy—was his brainchild in 1905, and for a decade and a half he stood practically alone in its defense. Einstein came up with most of what physicists now recognize as the essential features of quantum physics, such as light's peculiar ability to act as both particle and wave, and it was his thinking about wave physics that Erwin Schrödinger built on to develop the most widely used formulation of quantum theory in the 1920s. Nor was Einstein antirandomness. In 1916 he showed that when atoms emit photons, the timing and direction of emission are random. "This goes against the popular image of Einstein as an adversary to probability," says philosopher Jan von Plato of the University of Helsinki.

But Einstein and his contemporaries faced a serious problem. Quantum phenomena are random, but quantum *theory* is not. The Schrödinger equation is 100 percent deterministic. It describes a particle or system of particles using a so-called wave function, which expresses particles' wave nature and accounts for the undulating patterns that collections of particles can form. The equation predicts what happens to the wave function at every moment with complete certainty. In many ways, the equation is *more* deterministic than Newton's laws of motion: it does not lead to muddles such as singularities (where quantities become infinite and thus indescribable) or chaos (where motion becomes unpredictable).

The tricky part is that determinism of the Schrödinger equation is the determinism *of the wave function,* and the wave function is not directly observable, as the positions and velocities of particles are. Instead the wave function specifies the quantities that can be observed and the likelihood of each eventuality. The theory leaves open what exactly the wave function is and whether it should be taken literally as a real wave out there in the world. Thus, it also leaves open whether observed randomness is intrinsic to nature or just a facade. "People say that quantum mechanics is indeterministic, but that's too quick," says philosopher Christian Wüthrich of the University of Geneva in Switzerland.

Werner Heisenberg, another early pioneer of quantum theory, envisioned the wave function as a haze of potential existence. If it fails to pinpoint unequivocally where a particle is located, that is because the particle is not, in fact, located anywhere. Only when you observe the particle does it materialize somewhere. The wave function might have been spread out over a huge region of space, but at the instant the observation is made, it abruptly collapses to a narrow spike at a single position, and the particle pops up there. When you so much as look at a particle—bam!—it stops behaving deterministically and leaps to an end result like a kid grabbing a seat in musical chairs. No law governs collapse. There is no equation for it. It just happens.

Collapse became a core ingredient of the Copenhagen interpretation, the view of quantum mechanics named for the city where Bohr had his institute and Heisenberg did much of his early work. (Ironically, Bohr himself never accepted wave function collapse.) Copenhagen takes the observed randomness of

IN BRIEF

"I, at any rate, am convinced that He is not playing at dice," Albert Einstein wrote to his colleague Max Born in December 1926. Repeated over the years, his sound bite became the quintessential put-down of quantum mechanics and its embrace of randomness.

Closer examination, though, reveals that Einstein did not reject quantum mechanics or its indeterminism, although he did think—for solid scientific reasons—that the randomness could not be a fundamental feature of nature.

Today many philosophers argue that physics is *both* indeterministic and deterministic, depending on the level of reality being considered.

This view dissolves the much debated dilemma between determinism and free will. Even if everything that particles do is preordained, the choices that we make can be completely open because the low-level laws governing particles are not the same as the high-level laws governing human consciousness.

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quantum physics at face value, incapable of further explanation. Most physicists accepted it, if only because of a psychological anchoring effect: it was a good enough story, and it was the first.

Although Einstein was not antiquantum, he was definitely anti–Copenhagen interpretation. He recoiled from the idea that the act of measurement should cause a break in the continuous evolution of a physical system, and that was the context in which he began to complain about divine dice rolling. "It's that, specifically, that Einstein is lamenting in 1926 and not a blanket metaphysical assertion of determinism as an absolutely necessary condition," Howard says. "He's specifically in the thick of these arguments about whether or not wave function collapse introduces discontinuities."

Collapse could not be a real process, Einstein reasoned. It would require instantaneous action at a distance—a mysterious mechanism ensuring that, say, the left side and right side of a wave function both collapse to the same narrow spike even when no force is coordinating them. Not just Einstein but every physicist of his day thought such a process impossible; it would operate faster than light, in apparent violation of relativity theory. In effect, quantum mechanics does not just give you dice to play with. It gives you pairs of dice that always come up doubles, even if you roll one in Vegas and the other on Vega. For Einstein, it seemed obvious that the dice must be loaded—possessing hidden attributes that fix their outcome in advance. But Copenhagen denied any such thing, implying the dice really do affect each other instantly across the vastness of space.

Einstein was further troubled by the power that Copenhagen accorded to measurement. What is a measurement, anyway? Is it something that only conscious beings or tenured professors can do? Heisenberg and other Copenhagenists failed to elaborate. Some suggested that we create reality in the act of observing it—an idea that sounds poetic, perhaps a little too poetic. Einstein also thought it took a lot of chutzpah for Copenhagenists to claim that quantum mechanics was complete, a final theory never to be superseded. He regarded all theories, including his own, as stepping-stones to something greater.

In fact, Howard argues that Einstein would have been happy to entertain indeterminism as long as his concerns were addressed—if, for example, someone could spell out what a measurement was and how particles could stay in sync without acting at a distance. As a sign that Einstein considered indeterminism a secondary concern, he made the same demands of deterministic alternatives to Copenhagen and rejected them, too. Another historian, Arthur Fine of the University of Washington, thinks Howard overstates Einstein's receptiveness to indeterminism but agrees that the man's thinking was more solidly grounded than the dice-playing sound bite has led generations of physicists to assume.

RANDOM THOUGHTS

IF YOU TUG ON COPENHAGEN'S LOOSE ENDS, Einstein thought, you should find that quantum randomness is like every other type of randomness in physics: the product of deeper goings-on. The dancing of a dust mote in a shaft of sunlight betrays the complex motions of unseen air molecules, and the emission of a photon or radioactive decay of a nucleus is analogous, Einstein figured. In his estimation, quantum mechanics is a broad-brush theory that expresses the overall behavior of nature's building blocks but lacks the resolution to capture individual cases. A deeper, more complete theory would explain the motion in full without any mysterious jumps.

In this view, the wave function is a collective description, like saying that a fair die, repeatedly tossed, will land roughly the same number of times on each side. Wave function collapse is not a physical process but the acquisition of knowledge. If you roll a six-sided die and it lands on, say, four, the range of one to six "collapses" to the actual outcome of four. A godlike demon, able to track all the atomic details affecting the die—the exact way your hand sends the cube tumbling across the table—would never speak of collapse.

Einstein's intuitions were backed up by his early work on the collective effects of molecular motion—studied by the branch of physics known as statistical mechanics—in which he had demonstrated that physics could be probabilistic even when the underlying reality was deterministic. In 1935 Einstein wrote to philosopher Karl Popper, "I do not believe that you are right in your thesis that it is impossible to derive statistical conclusions from a deterministic theory. Only think of classical statistical mechanics (gas theory, or the theory of Brownian movement)."

EINSTEIN WAS TRYING TO EXPLAIN RANDOMNESS, NOT EXPLAIN IT AWAY.

The probabilities in Einstein's way of thinking were just as objective as those in the Copenhagen interpretation. Although they did not appear in the fundamental laws of motion, they expressed other features of the world; they were not merely artifacts of human ignorance. Einstein gave Popper the example of a particle that moves around a circle at steady speed; the chance of finding the particle in a given arc of the circle reflects the symmetry of its path. Similarly, a die has a one-sixth chance of landing on a given side because it has six equal sides. "He did understand better than most at that time that there was significant physical content in the details of statistical-mechanical probabilities," Howard says.

Another lesson of statistical mechanics was that the quantities we observe do not necessarily exist on a deeper level. For instance, a gas has a temperature, but a single gas molecule does not. By analogy, Einstein came to believe that a subquantum theory needed to mark a radical break from quantum mechanics. In 1936 he wrote, "There is no doubt that quantum mechanics has seized hold of a beautiful element of truth.... However, I do not believe that quantum mechanics will be the *starting point* in the search for this basis, just as, vice versa, one could not go from thermodynamics (resp. statistical mechanics) to the foundations of mechanics." To fill in that deeper level, Einstein sought a unified field theory, in which particles derive from structures that look nothing like particles. In short, conventional wisdom is wrong that Einstein repudiated the randomness of quantum physics. He was trying to explain the randomness, not to explain it away.

DO YOUR LEVEL BEST

ALTHOUGH EINSTEIN'S OVERALL PROJECT FAILED, his basic intuition about randomness still holds: indeterminism can emerge from determinism. The quantum and subquantum lev-

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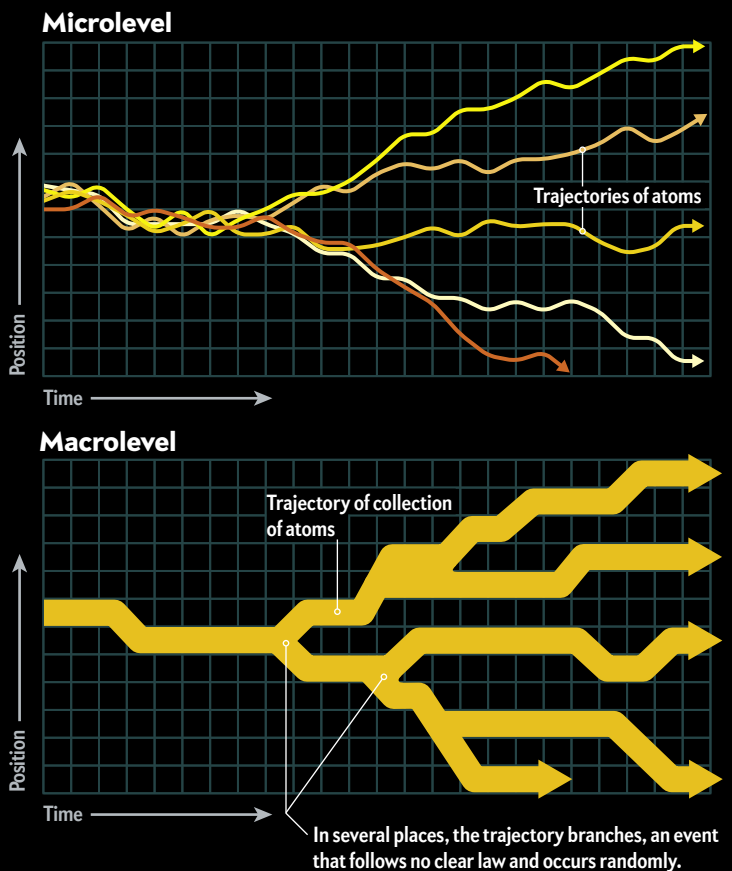
Reality's Many Realms

Is the world deterministic or indeterministic? The answer depends not only on the basic laws of motion but also on the level at which a system is described. Consider five atoms in a gas moving deterministically (*top plot*). They start at nearly the same location and gradually spread out. On a macroscopic level (*bottom plot*), though, one would not see individual atoms but an amorphous puff of gas. After a time, the gas might split at random into multiple puffs. This macrolevel randomness is not an artifact of an observer's ignorance about the microlevel; it is an objective feature of nature, reflecting how atoms agglomerate. Analogously, Einstein suspected that a deterministic subrealm of the universe leads to the randomness of the quantum realm.



SOURCE: "EMERGENT CHANCE," BY CHRISTIAN LIST AND MARCUS PIVATO, IN *THE PHILOSOPHICAL REVIEW*, VOL. 124, NO. 1; JANUARY 2015

els—or any other pair of levels in the hierarchy of nature—consist of distinct types of structures, so they abide by different types of laws. The laws governing one level can leave a genuine element of randomness even if the laws underneath it are completely regimented. "A deterministic microphysics does not induce a deterministic macrophysics," says philosopher Jeremy Butterfield of the University of Cambridge.

Think of a die at the atomic level. It can be constructed from zillions of atomic configurations that look utterly indistinguishable to the eye. If you track any one of these configurations as the cube is rolled, it will lead to a specific outcome—deterministically. In some configurations, the die ends up showing one dot; in others, two; and so on. Therefore, a single macroscopic condition (being rolled) can lead to multiple possible macroscopic outcomes (showing one of six faces) [*see box at left*]. "If we describe the die at a macrolevel, we can think of it as a stochastic system, which admits objective chance," says List, who has studied the meshing of levels with Marcus Pivato, a mathematician at the University of Cergy-Pontoise in France.

Although the higher level builds (in the jargon, "supervenes") on the lower one, it is autonomous. To describe dice, you need to work at a level where dice exist, and when you do so, you cannot help but neglect atoms and their dynamics. If you cross one level with another, you commit the fallacy of a category mistake, which is like asking about the political affiliations of a tuna sandwich (to use an example from philosopher David Z Albert of Columbia University). "When we have phenomena that can be described at multiple levels, we have to be conceptually very careful in not mixing levels," List says.

For this reason, the die roll is not merely apparently random, as people sometimes say. It is truly random. A godlike demon might brag that it knows exactly what will happen, but it knows only what will happen *to the atoms*. It does not even know what a die is, because that is higher-level information. The demon never sees a forest, only trees. It is like the protagonist of Argentine writer Jorge Luis Borges's short story "Funes, the Memorious," a man who remembers everything and grasps nothing. "To think is to forget a difference, to generalize, to abstract," Borges wrote. For the demon to know which side the die lands on, you have to tell it what to look for. "The demon would only be able to infer the higher-level history if the demon was given our specification of how we partition the physical level," List says. Indeed, the demon might well come to envy our mortal perspective.

The level logic works the other way, too. Indeterministic microphysics can lead to deterministic macrophysics. A baseball can be made of particles behaving randomly, yet its flight is entirely predictable; the quantum randomness averages out. Likewise gases consist of molecules executing enormously complicated—and effectively indeterministic—movements, yet their

Graphic by Jen Christiansen

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temperature and other properties follow laws that are dead simple. More speculatively, some physicists such as Robert Laughlin of Stanford University suggest that the lower level is utterly irrelevant. The building blocks could be anything and still produce the same collective behavior. After all, systems as diverse as water molecules, stars in a galaxy and cars on a highway obey the same laws of fluid flow.

FREE AT LAST

WHEN YOU THINK IN TERMS OF LEVELS, the worry that indeterminism might mark the end of science evaporates. There is no big wall around us, cordoning off a law-abiding chunk of the universe from the anarchic and inexplicable beyond. Instead the world is a layer cake of determinism and indeterminism. The earth's climate, for example, supervenes on Newton's deterministic laws of motion, but weather reports are probabilistic, whereas seasonal and longer-term climate trends are again predictable. Biology, too, supervenes on deterministic physics, but organisms and ecosystems require different modes of description, such as Darwinian evolution. "Determinism doesn't explain everything," says Tufts University philosopher Daniel C. Dennett. "Why are there giraffes? Because it was 'determined' that there would be?"

Human beings are embedded within this layer cake. We have the powerful sense of free will. We often do the unpredictable, and in most of life's decisions, we feel we were capable of doing otherwise (and often wish we had). For millennia, so-called philosophical libertarians—not to be confused with the political kind—have argued that human freedom requires particle freedom. Something must break the deterministic flow of events, such as quantum randomness or the "swerves" that some ancient philosophers thought atoms can undergo.

The trouble with this line of thought is that it would free the particles but leave us enslaved. Whether your decision was preordained at the big bang or made by a mutinous particle, it is not your decision. To be free, we need indeterminism not at the particle level but at the human level. And that is possible because the human and particle levels are autonomous. Even if everything you do can be traced to earlier events, you can be the author of your actions because neither you nor the actions exist at the level of matter, only at the macrolevel of mind. "This macroindeterminism riding on microdeterminism may secure free will," Butterfield says. Macroindeterminism is not the cause of your decision. It *is* your decision.

Some might complain that you are still a puppet of the laws of nature, that your freedom is an illusion. But the word "illusion" itself conjures up desert mirages and ladies sawed in half: things that are unreal. Macroindeterminism is not like that. It is quite real, just not fundamental. It is comparable to life. Individual atoms are completely inanimate, yet enormous masses of them can live and breathe. "Anything to do with agents, their intentional states, their decisions and choices: none of this features in the conceptual repertoire of fundamental physics, but that doesn't mean those phenomena aren't real," List observes. "It just means that those are very much higher-level phenomena."

It would be a category mistake, not to mention completely unenlightening, to describe human decisions as the mechanics of atoms in your brain. Instead you need to use all the concepts of psychology: desire, possibility, intention. Why did I choose water over wine? Because I wanted to. My desire explains my action. Most of the times that we ask "Why?" we are seeking someone's motivations rather than the physics backstory. Psychological explanations presume the kind of indeterminism that List is talking about. For example, game theorists model human decisions by laying out the range of options and showing which one you will select if you are acting rationally. Your freedom to choose a certain option steers your choice even if you never plump for that option.

To be sure, List's arguments do not explain free will fully. The hierarchy of levels opens up space for free will by separating psychology from physics and giving us the opportunity to do the unexpected. But we have to seize the opportunity. If, for example, we made every decision on a coin toss, that would still count as macroindeterminism but would hardly qualify as free will in any meaningful sense. Some people's decision-making may be so debilitated that they cannot be said to act freely.

This way of thinking about determinism also makes sense of an interpretation of quantum theory that was developed in the years after Einstein's death in 1955: the many-worlds interpretation. Advocates argue that quantum mechanics describes a collection of parallel universes—a multiverse—that behaves deterministically in the large but looks indeterministic to us because we are able to see only a single universe. For instance, an atom might emit a photon to the left or to the right; quantum theory leaves the outcome open. According to the many-worlds interpretation, that is because the same situation arises in a zillion parallel universes; in some, the photon goes deterministically left, and in others, it goes right. Not being able to tell which of those universes we reside in, we cannot predict what will happen, so the situation from the inside looks inexplicable. "There is no true randomness in the cosmos, but things can appear random in the eye of the beholder," says cosmologist Max Tegmark of the Massachusetts Institute of Technology, a prominent proponent of this view. "The randomness reflects your inability to self-locate."

That is very similar to saying that a die or brain could be constructed from any one of countless atomic configurations. The configurations might be individually deterministic, but because we cannot know which one corresponds to our die or our brain, we have to think of the outcome as indeterministic. Thus, parallel universes are not some exotic idea out there in the cosmos. Our body and brain are little multiverses, and it is the multiplicity of possibility that endows us with freedom. SA

George Musser is a contributing editor at *Scientific American* and author of *Spooky Action at a Distance* (Farrar, Straus and Giroux, 2015) and *The Complete Idiot's Guide to String Theory* (Alpha, 2008).

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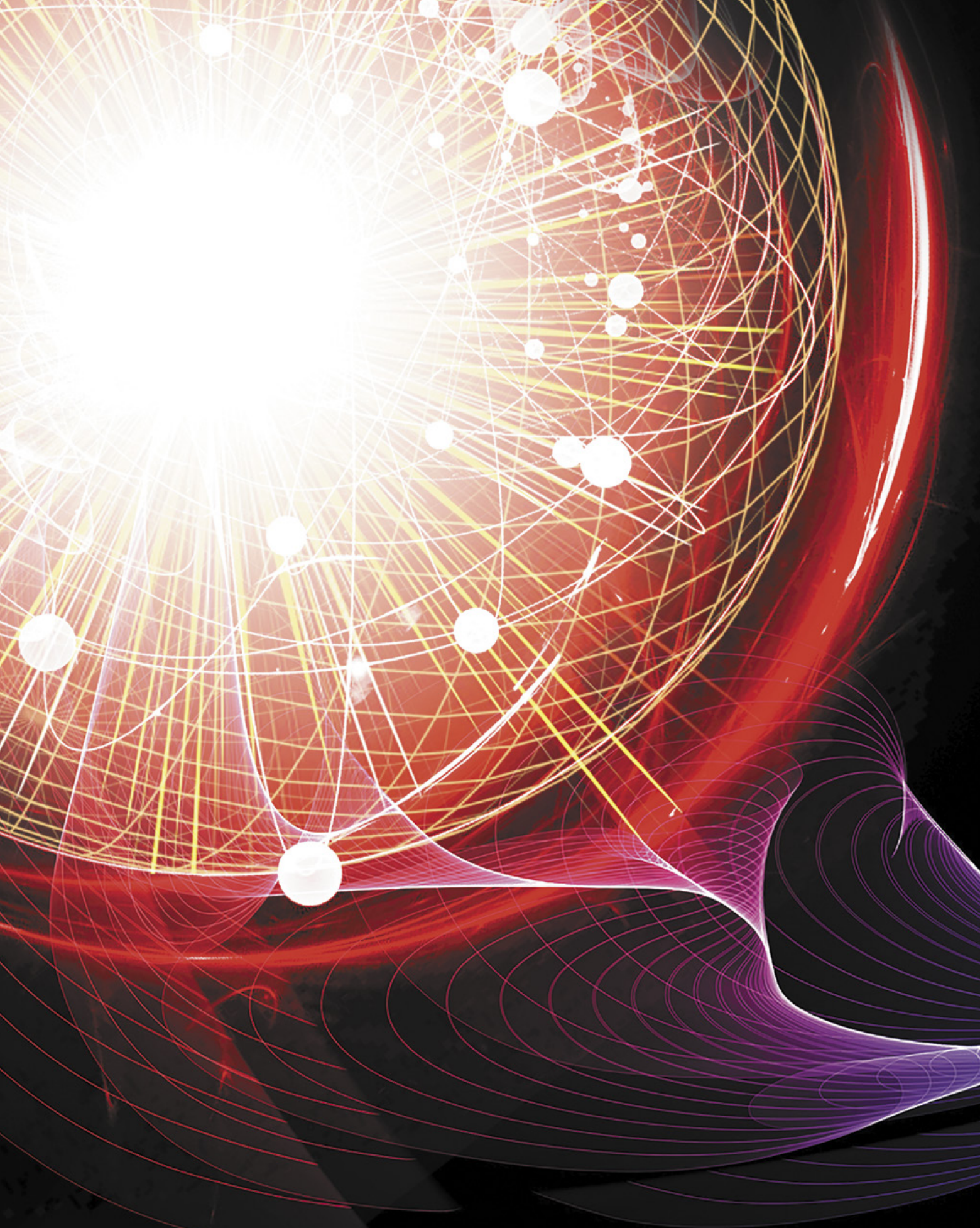

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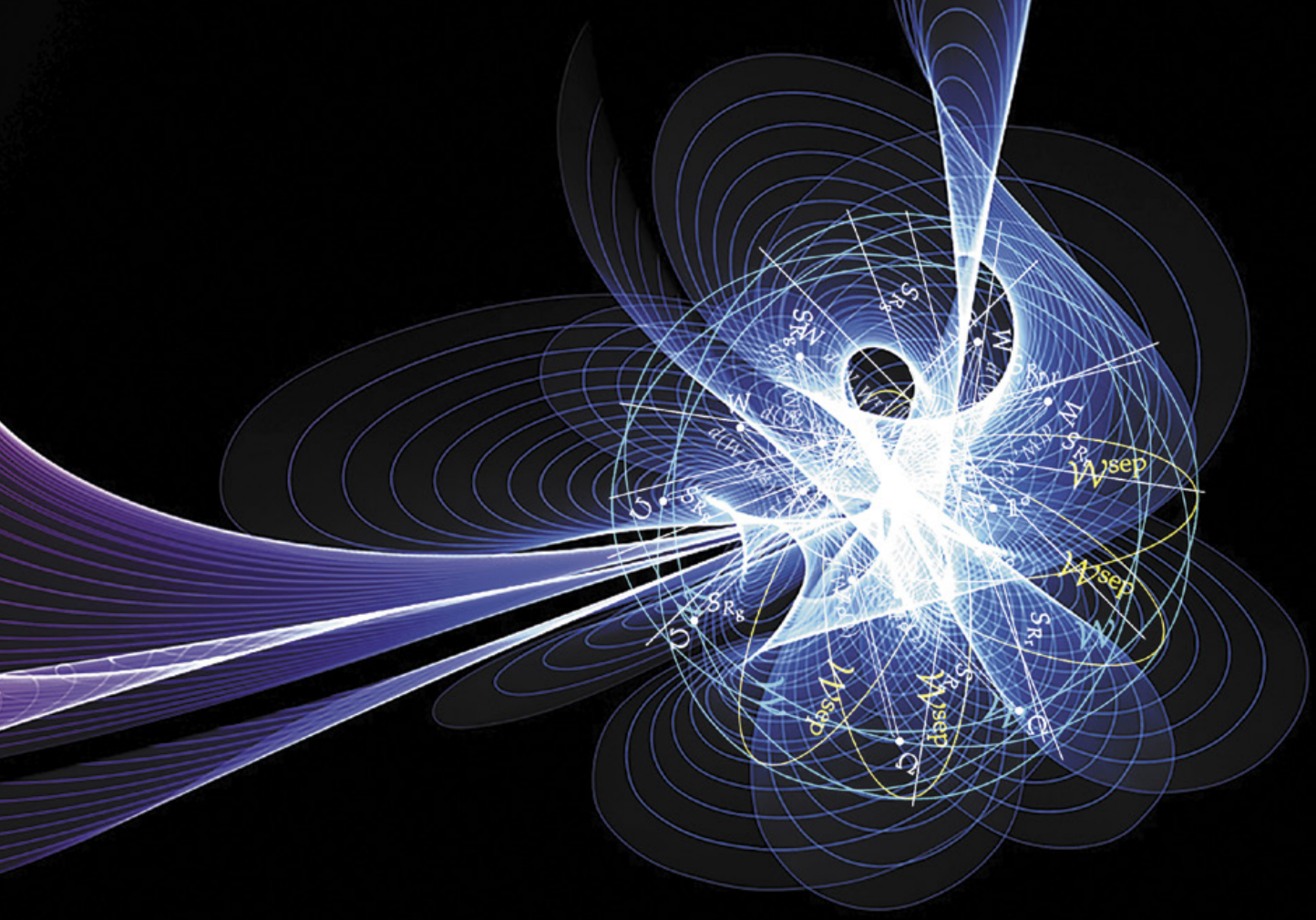
SPOOKY ACTION

Recent experiments quash the hope that the unsettling phenomenon of quantum entanglement can be explained away

By Ronald Hanson and Krister Shalm

Illustration by Kenn Brown and Chris Wren, Mondolithic Studios



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Not all revolutions start big. In the case of quantum mechanics, a quiet one began in 1964, when physicist John Bell published an equation. This equation, in the form of a mathematical inequality, proposed a test to address deep philosophical questions that troubled many of the early founders of quantum mechanics.

The issue was whether particles separated by vast distances could retain a connection so that measurements performed on one affect the other. According to classical physics, this should be impossible. But under quantum theory, it happens all the time. Through his equation, Bell proposed a way to determine whether the universe could actually be that strange.

Over the past half a century his simple equation has profoundly changed the way we think about quantum theory. Today many of the quantum technologies that physicists are inventing owe their beginnings to Bell's test. Yet it was not until 2015, more than 50 years after Bell proposed his inequality, that scientists were able to verify the predictions of Bell's theorem in the most complete manner possible. These experiments close a quest that has spanned generations and mark the start of a new era in developing quantum technologies.

HIDDEN VARIABLES

TO UNDERSTAND BELL'S EQUATION, we must go back to the roots of quantum mechanics. This set of rules describes the behavior of light and matter at the smallest scales. Atoms, electrons, photons and other subatomic particles act differently from things we experience in our everyday lives. One of the major deviations is that these small particles exist in uncertain states. Take an electron's spin, for example. If an electron whose spin is sideways passes through a magnetic field oriented up and down, half the time it will veer upward and half the time it will veer downward, but the outcome is truly random. Compare this to a coin flip. We might think that flipping a coin is equally random, but if we knew precisely the mass of the coin, how much force was used to flip it and all the details about the air currents hitting it, we would be able to predict exactly how the coin would land. Electron spin is different, however. Even if we had perfect knowledge about all the properties of the electron and its spin before it passes through the magnetic field, quantum fuzziness prevents us from knowing which way it will go (we can, however, calculate the *probability* of it going up or down). When scientists actually measure a quantum system, though, all these possibilities cease to exist somehow, and a single outcome is decided—the electron ends up having a spin that is oriented either up or down.

When physicists formulated quantum theory in the early 20th century, some of its founding members, such as Albert Einstein and Erwin Schrödinger, felt uncomfortable with the fuzziness of quantum states. Perhaps, they thought, nature is not really fuzzy, and a theory that goes beyond quantum mechanics could exactly predict the behavior of particles. Then it would be possible to foresee the outcome of a measurement of the spin of an electron in the same way it is possible to know exactly how a coin will land if you have enough information.

Schrödinger introduced the idea of entanglement (*Verschränkung* in German) to describe quantum fuzziness spread across two or more particles. According to quantum theory, properties of particles can be entangled such that their joint value is precisely known, but the individual values remain completely uncertain. An analogy would be two dice that, when rolled, would each yield a random result but together always add up to 7. Schrödinger used the idea of entanglement in a famous thought experiment in which the fuzziness of the state of an atom becomes entangled with a cat being dead or alive. Surely any cat is either dead or alive and not in an absurd limbo in between, Schrödinger reasoned, and therefore we should question the notion that atoms can be fuzzy at all.

Einstein, with his collaborators Boris Podolsky and Nathan Rosen (known together as EPR), took the argument a step further by analyzing two entangled electrons that are far apart. Imagine that the spins of the particles are entangled such that when measured along the same orientation, opposite values will always result. For instance, if scientists measure one electron spin and find it to be pointing up, the other will point down. Such correlations are certainly surprising when the electrons are far enough apart that it is impossible for them to communicate at the speed of light before their individual spins are measured. How does the second particle know that the first one was up? Einstein famously called this synchronization "spooky actions at a distance."

The EPR analysis of this case, published in 1935 in a now classic paper, started from two very reasonable assumptions. First, if scientists can predict a measurement outcome with certainty, there must be some property in nature that corresponds to this outcome. Einstein named these properties "elements of

IN BRIEF

In 1964 physicist John Bell discovered that the phenomenon of quantum entanglement—where two particles can retain a "spooky" connection even when far apart—leads to a mathematical conflict with our intuitive picture of nature.

Since Bell's proposal, experimenters have staged many versions of his test. Most results seemed in agreement with the existence of entanglement. Yet each of these experiments has contained loopholes that make it possible for "hidden variables" to act behind the scenes, producing results that masquerade as entanglement.

Finally, in 2015, several groups conducted the first loophole-free Bell tests, ruling out any local hidden variable explanation.

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reality." For example, if we know that an electron's spin is up, we can predict with certainty that if it travels through an appropriate magnetic field it will always be deflected upward. In this situation, the electron's spin would be an element of reality because it is well defined and not fuzzy. Second, an event in one place cannot instantaneously affect a faraway event; influences cannot travel faster than the speed of light.

Taking these assumptions, let us analyze two entangled electrons held at distant places by two people, Alice and Bob. Suppose Alice measures her electron spin along the z direction. Because of the perfect anticorrelation, she immediately knows what the outcome will be if Bob measures his electron spin along z as well. According to EPR, the z component of Bob's electron spin would thus be an element of reality. Similarly, if Alice decides to measure the spin along the x direction, she would know with certainty the outcome of a measurement on Bob's electron spin along x. In this case, the x component of Bob's electron spin would be an element of reality. But because Alice and Bob are far apart, Alice's decision to measure along the z direction or the x direction cannot influence what happens at Bob's. Therefore, to account for the perfect anticorrelations predicted by quantum theory, the value of Bob's electron spin must be perfectly predictable both along the z direction and the x direction. This appears to contradict quantum theory, which states, through the so-called Heisenberg uncertainty principle, that the spin can have a well-defined value along a single direction only and must be fuzzy along the others.

This conflict led EPR to conclude that quantum theory is incomplete. They suggested that it might be possible to resolve the contradiction by supplementing the theory with extra variables. In other words, there might be a deeper theory that goes beyond quantum mechanics in which the electrons possess extra properties that describe how they will behave when jointly measured. These extra variables might be hidden from us, but if we had access to them, we could predict exactly what would happen to the electrons. The apparent fuzziness of quantum particles is a result of our ignorance. Physicists call any such successor to quantum mechanics that contains these hidden variables a "local hidden variable theory." The "local" here refers to the hidden signals not being able to travel faster than the speed of light.

BELL'S TWIST

EINSTEIN DID NOT QUESTION the predictions of quantum mechanics itself; rather he believed there was a deeper truth in the form of hidden variables that govern reality. After the 1935 EPR paper, interest in these foundational issues in quantum mechanics died down. The possibility of hidden variables was seen as a philosophical question without any practical value—the predictions of theories with and without hidden variables appeared to be identical. But that changed in 1964, when Bell startlingly showed that in certain circumstances hidden variable theories and quantum mechanics predict different things. This revelation meant it is possible to test experimentally whether local hidden variable theories—and thus Einstein's hoped-for deeper truth of nature—can really exist.

Bell analyzed the EPR thought experiment but with one twist: he let Alice and Bob measure their electron spins along any possible direction. In the traditional experiment, Alice and Bob must measure along the same direction and therefore find that their results are 100 percent correlated—if Alice measures up, then Bob always measures down. But if Alice and Bob are sometimes measuring along different axes, sometimes their outcomes are not synchronized, and that is where the differences between quantum theory and hidden variable theories come in. Bell showed that for certain sets of directions, the correlations between the outcomes of Alice's and Bob's measurements would be stronger according to quantum theory than according to any local hidden variable theory—a difference known as Bell's inequality. These differences arise because the hidden variables cannot influence one another faster than the speed of light and therefore are limited in how they can coordinate their efforts. In contrast, quantum mechanics allows the two electrons' spins to exist jointly in a single entangled fuzzy state that can stretch over vast distances. Entanglement causes quantum theory to predict correlations that are up to 40 percent stronger.

Bell's theorem completely changed physicists' thinking. It showed a mathematical conflict between Einstein's view and quantum theory and outlined a powerful way for experimentally testing the two. Because Bell's theorem is a mathematical inequality that limits how high correlations can be under any local hidden variable theory, experimental data that exceed these bounds—in other words, that "violate" Bell's inequality—will show that local hidden variable theories cannot describe nature.

Soon after Bell's publication, physicists John Clauser, Michael Horne, Abner Shimony and Richard Holt (known as CHSH) found similar inequalities that were easier to test in experiments. Researchers performed the first trials in the late 1960s, and since then experiments have come closer and closer to the ideal of Bell's proposed setup. The experiments have found correlations that violate Bell's inequality and seemingly cannot be explained by local hidden variable theories. Until 2015, though, all experiments necessarily relied on one or more additional assumptions because of imperfections in the setups. These assumptions provide loopholes that local hidden variable theories could in principle use to pass the test.

In virtually all such experiments in the 20th century, scientists generated entangled photons at a source and sent them to measurement stations (standing in for Alice and Bob). The Alice and Bob stations each measured their respective photon along one of two orientations, noting its polarization—the direction in which the photon's electric field oscillates (polarization can be thought of as the spin of a photon). The scientists then calculated the average correlations between the two stations' outcomes and plugged those into Bell's equation to check whether the results violated the inequality.

TESTS WITH CAVEATS

THE FIRST SERIES OF EXPERIMENTS used fixed measurement directions. In these cases, there is ample time for hidden variables (using knowledge of the measurement directions on either side) to influence the outcomes. That is, hidden signals could tell Bob which direction Alice used to measure her photon without traveling faster than light. This so-called locality loophole means that a hidden variable theory could match the quantum correlations. In 1982 French physicist Alain Aspect and his co-workers performed a test where the photons were sent to opposite ends of a large room and their polarization

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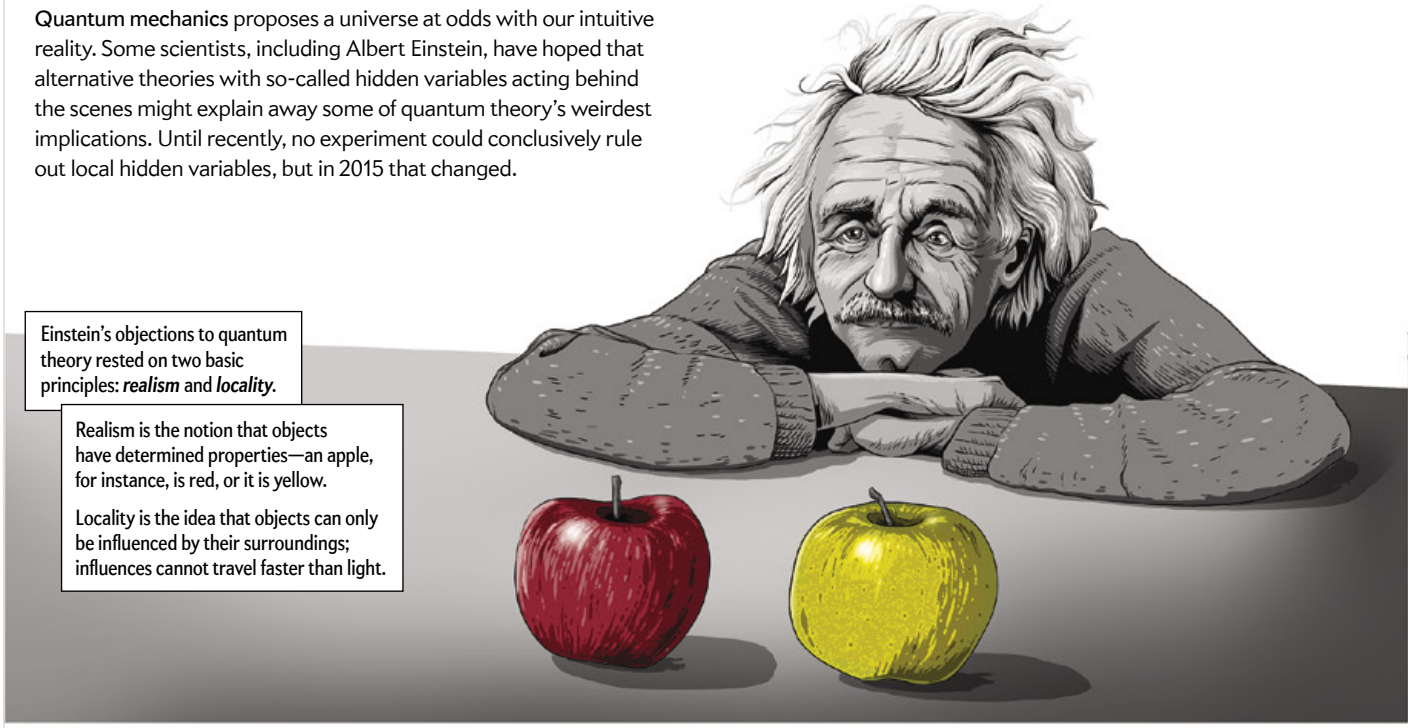
Closing All the Loopholes

Quantum mechanics proposes a universe at odds with our intuitive reality. Some scientists, including Albert Einstein, have hoped that alternative theories with so-called hidden variables acting behind the scenes might explain away some of quantum theory's weirdest implications. Until recently, no experiment could conclusively rule out local hidden variables, but in 2015 that changed.



Einstein's objections to quantum theory rested on two basic principles: ***realism*** and ***locality***.

Realism is the notion that objects have determined properties—an apple, for instance, is red, or it is yellow.

Locality is the idea that objects can only be influenced by their surroundings; influences cannot travel faster than light.

Yet the theory of quantum mechanics suggests that reality is much weirder than that.

According to quantum mechanics, a particle can be in two states at the same time.

For example, a quantum apple …

Particles can even be entangled with one another. That is, if you look at one apple and find it red, the other instantly becomes yellow.

Entanglement exists no matter the distance between particles.

Einstein refused to accept this concept, calling it "spooky actions at a distance."

He claimed there must be local hidden variables, unknown to observers, that control this entanglement because otherwise influences must be traveling faster than light.

Illustration by Matthew Twombly

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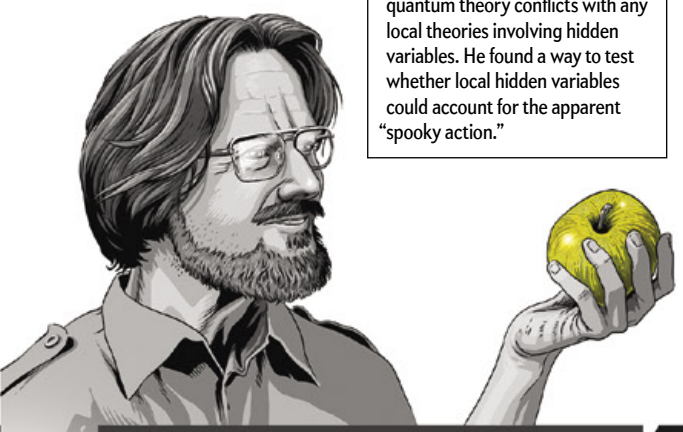
In 1964 John Bell discovered that quantum theory conflicts with any local theories involving hidden variables. He found a way to test whether local hidden variables could account for the apparent "spooky action."



The Bell test: Two observers would make separate measurements of two supposedly entangled particles. Bell calculated the maximum amount of correlation that could arise between the two observers' findings if local hidden variables limited by the speed of light were at work.

Experimenters soon got to work putting the test into action. But two loopholes left some leeway for hidden variables.

1. Locality loophole
The measurement stations are close enough to allow communication with each other at sub–light speed during a test.

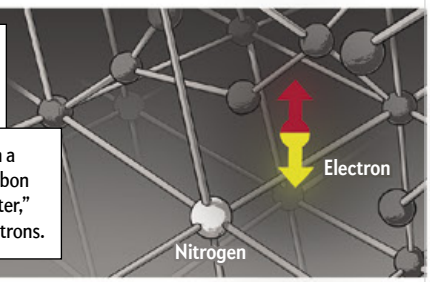
2. Detection loophole
The detectors are only able to measure some but not all the entangled particles.

In 2015 several groups of scientists devised versions of the Bell test that close both loopholes.

One, at the Delft University of Technology, starts with two tiny diamonds.

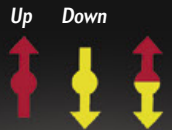
In the nearly perfect carbon lattice of a diamond, there exists a flaw, the occasional nitrogen atom.

In some places, next to such a nitrogen atom there is a carbon atom missing, a "defect center," which acts as a trap for electrons.



Electrons have a spin . . .

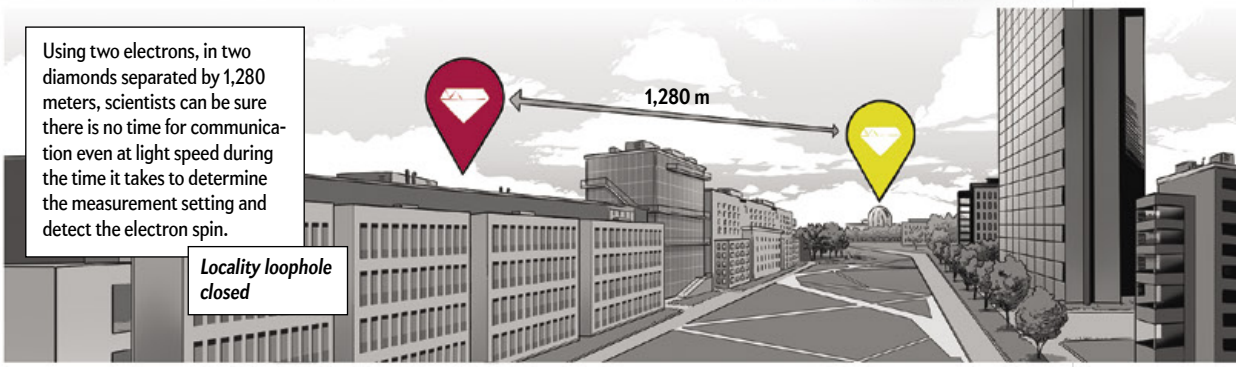
Up *Down*



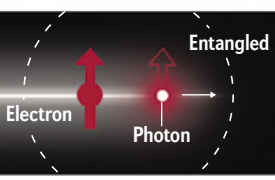
Or in a *superposition*, both up and down.

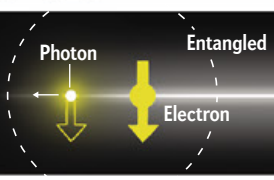
Using two electrons, in two diamonds separated by 1,280 meters, scientists can be sure there is no time for communication even at light speed during the time it takes to determine the measurement setting and detect the electron spin.

Locality loophole closed



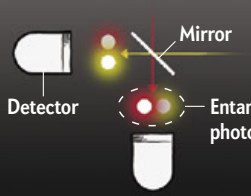
Scientists use lasers to excite the electrons, which then emit photons that are entangled with the spin of the electrons.





Those photons travel across campus until they meet each other at detectors.

When the photons meet, they become entangled. By extension, their distant respective electrons—which are easier to detect and measure than photons—also become entangled.



Detection loophole closed

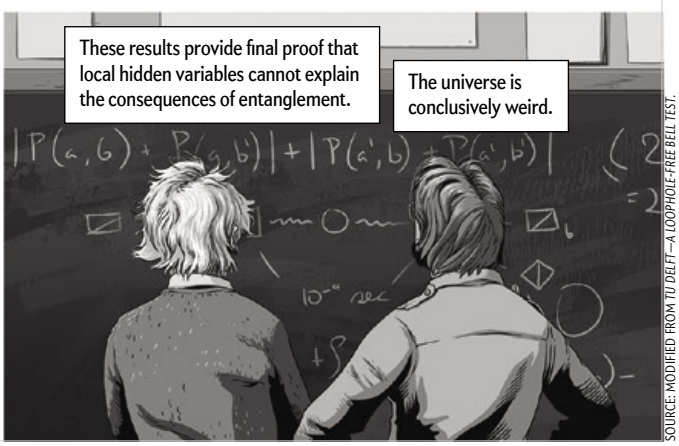
For the first time, a loophole-free Bell test

At Delft, scientists ran 245 trials in which a pair of electrons 1,280 meters apart were entangled. They measured the particles in every case and found 80 percent were correlated—significantly more than would be possible with local hidden variables.

Experiments in the U.S., Austria and Germany found similar results.

These results provide final proof that local hidden variables cannot explain the consequences of entanglement.

The universe is conclusively weird.



SOURCE: MODIFIED FROM *TU DELFT—A LOOPHOLE-FREE BELL TEST.* TEXT BY MICHEL VAN BAAL AND GRAPHICS BY SCIXEL. TU DELFT, 2015

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measured. While these entangled photons were in flight, the polarization angle of the measurement device changed periodically. In the late 1990s Anton Zeilinger, now at the University of Vienna, and his colleagues further improved this strategy by using truly random (as opposed to periodic) polarization-measurement directions. In addition, these measurement directions were determined very shortly before the measurements took place, so hidden signals would have had to travel faster than light to affect this experiment. The locality loophole was firmly closed.

These experiments had one drawback, however: photons are hard to work with. Most of the time the tests got no answer at all, simply because the photons were not created in the first place or were lost along the way. The experimenters were forced to assume that the trials that worked were representative of the full trial set (the "fair sampling assumption"). If this assumption was dropped, the results would not violate Bell's inequality. It is possible that something different was happening in the trials where photons were lost, and if their data were included, the results would not be in conflict with local hidden variable theories. Scientists were able to close this so-called detection loophole in this century by giving up photons and using matter, such as trapped ions, atoms, superconducting circuits and nuclei in diamond atoms, which can all be entangled and measured with high efficiency. The problem is that in these cases the particles were all located extremely close to one another, leaving the locality loophole open. Thus, although these Bell tests were ingenious, they could all, at least in principle, be explained by a local hidden variable theory. A Bell test with all the loopholes closed simultaneously became one of the grandest challenges in quantum science.

LOCAL HIDDEN VARIABLES CANNOT EXPLAIN THE CONSEQUENCES OF ENTANGLEMENT. THE UNIVERSE IS CONCLUSIVELY WEIRD.

Thanks to rapid progress in scientists' ability to control and measure quantum systems, it became possible in 2015, 80 years after the EPR paper and 51 years after Bell's equation, to carry out a Bell test in the ideal setting, often referred to as a loophole-free Bell test. In fact, within a short span of time, four different groups found results that violated Bell's inequality with all loopholes closed—providing ironclad evidence against local hidden variable theories.

CLOSING THE LOOPHOLES

ONE OF US (Hanson) and his collaborators performed the first experiment to close all loopholes at the Delft University of Technology in the Netherlands using a setup [*see box on preceding page*] that closely resembles the original EPR concept. We entangled the spins of two electrons contained inside a diamond, in a space called a defect center, where a carbon atom should have been but was missing. The two entangled electrons were in different laboratories across campus, and to make sure no communication was possible between them, we used a fast random-number generator to pick the direction of measurement. This measurement was finished and locally recorded on a hard drive before any information from the measurement on the other side could have arrived at light speed. A hidden signal telling one measuring station which direction the other had used would not have had time to travel between the labs, so the locality loophole was firmly closed.

These strict timing conditions required us to separate the two electrons by more than a kilometer, about two orders of magnitude farther apart than the previous world record for entangled matter systems. We achieved this separation by using a technique called entanglement swapping, in which we first entangle each electron with a photon. We then send the photons to meet halfway between the two labs on a semitransparent mirror where we have placed detectors on either side. If we detect the photons on different sides of the mirror, then the spins of the electrons entangled with each photon become entangled themselves. In other words, the entanglement between the electrons and the photons is transferred to the two electrons. This process is prone to failure—photons can be lost between the diamonds and the mirror, just as in the earlier photon-based experiments. But we start a Bell trial only if both photons are detected; thus, we deal with photon loss beforehand. In this way, we close the detection loophole because we do not exclude the findings of any Bell test trials from our final results. Although the photon loss related to the large separation in our case does not limit the quality of the entanglement, it does severely restrict the rate at which we can conduct Bell trials—just a few per hour.

After running the experiment nonstop for several weeks in June 2015, we found Bell's inequality was violated by as much as 20 percent, in full agreement with the predictions of quantum theory. The probability that such results could have arisen in any local hidden variable model—even allowing the devices to have maliciously conspired using all available data—was 0.039. A second experimental run conducted in December 2015 found a similar violation of Bell's inequalities.

In the same year, three other groups performed loophole-free Bell tests. In September physicists at the National Institute of Standards and Technology (NIST) and their colleagues, led by one of us (Shalm), used entangled photons, and in the same month Zeilinger's group did so as well. Not too long after, Harald Weinfurter of Ludwig Maximilian University of Munich and his team used rubidium atoms separated by 400 meters in a scheme similar to that of the Hanson group (the results were published in 2017).

Both the NIST and Vienna teams entangled the polarization state of two photons by using intense lasers to excite a special crystalline material. Very rarely, about one in a billion of the laser photons entering the crystal underwent a transformation and split into a pair of daughter photons whose polarization states were entangled. With powerful enough lasers, it was possible to generate tens of thousands of entangled photon pairs per second. We then sent these photons to distant stations (sep-

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arated by 184 meters in the NIST experiment and 60 meters in the Vienna experiment) where we measured the polarization states. While the photons were in flight toward the measurement stations, our system decided which direction to measure their polarization in such a way that it would be impossible for any hidden variables to influence the results. The locality loophole is therefore closed. The most challenging aspect of using photons is preventing them from being lost, as we must detect more than two thirds of the photons we create in our setup to avoid the detection loophole. Most conventional single-photon detectors operate at around 60 percent efficiency—a nonstarter for this test. But at NIST we developed special single-photon detectors, made of cold superconducting materials, capable of observing more than 90 percent of the photons that reach it. Thus, we closed the detection loophole as well.

Repeating these polarization measurements on many different entangled photon pairs more than 100,000 times per second, we were able to quickly accumulate statistics on the correlations between the photon polarization states. The correlations observed in both experiments were much stronger than those predicted by hidden variable theories. In fact, the probability that the NIST results could have arisen by chance is on the order of one in a billion (even less likely than winning the Powerball lottery), and the chances are even smaller for the Vienna experiment. Today our NIST group regularly uses an improved version of our setup to violate Bell's inequalities to a similar degree in less than a minute, and future improvements will speed this up by two orders of magnitude.

HARNESSING ENTANGLEMENT

THESE EXPERIMENTS FORCE US TO CONCLUDE that any local hidden variable model, such as those Einstein advocated, is incompatible with nature. The correlations between particles we have observed defy our intuition, showing that spooky action does indeed take place.

Our results also hint at the remarkable power contained in entanglement that we may be able to put to use. A near-term application where loophole-free Bell tests can be useful is in generating randomness. Random numbers are a critical resource in many cryptographic and security techniques. If you can predict the next number a random-number generator will produce, you can hack many financial and communications systems. A good source of randomness that cannot be predicted is therefore of vital importance. Two of the most common ways to generate randomness are through mathematical algorithms or using physical processes. With mathematical algorithms, if you know the conditions used as a "seed," you can often predict the output perfectly. With physical processes, a detailed understanding of the underlying physics of the system is required. Miss even a single detail, and a hacker can exploit or control the randomness. The history of cryptography is littered with examples of both types of random-number generators being broken.

Quantum mechanics has handed us a gift, though. It is possible to "extract" the randomness inherent in quantum processes to produce true randomness. The correlations measured in a loophole-free Bell test can be distilled into a certifiably random string. Remarkably, it is possible to hand part of the experimental apparatus (the generation of the entangled particles) to a potential hacker to control. Even in this extreme case, it is possible to produce numbers that are as random as nature allows. In early 2018 our team at NIST was able to use our loophole-free Bell setup to extract 1,024 truly random bits from 10 minutes of experimental data. These bits were certified to be random to better than a part in one trillion. In contrast, it would take a conventional random-number generator several hundred thousand years to acquire enough data to directly measure the quality of their randomness to this level. We are working now to incorporate our random-number generator into a public randomness beacon. This tool could act as a time-stamped source of random numbers that is broadcast over the Internet at fixed intervals and can be used in security applications by anyone who needs it.

On a more general level, the techniques developed in loophole-free Bell experiments may enable fundamentally new types of communications networks. Such networks, often referred to as a quantum Internet, can perform tasks that are out of reach of classical information networks. A quantum Internet could enable secure communication, clock synchronization, quantum sensor networks, as well as secure access to remote quantum computers in the cloud. Another goal is "device-independent cryptography," in which (in close analogy to the randomness beacon) users can validate the secrecy of a shared key through a violation of Bell's inequalities.

The backbone of a future quantum Internet will be formed by entanglement links precisely like the setups used to test Bell's inequalities with diamond defect centers, trapped atoms and photons. In 2017 our team at Delft demonstrated a method to boost the quality of remote entangled spins, and in 2018 we improved the entangling rates by three orders of magnitude. Based on this progress, researchers are working toward a first rudimentary version of a quantum Internet that is scheduled to be realized among a few cities in the Netherlands in 2020.

Eight decades ago when quantum theory was being written, skeptics chafed at its apparent contradiction with the centuries of physical intuition that had been developed; now four experiments have dealt the final blow to that intuition. At the same time, these results have opened the door to exploit nature in ways that Einstein and Bell could not have foreseen. The quiet revolution that John Bell kicked off is now in full swing. SA

Ronald Hanson is a physicist at Delft University of Technology and scientific director of its QuTech research center, a collaboration with the Netherlands Organization for Applied Scientific Research (TNO), focused on quantum computing and quantum Internet technology.

Krister Shalm is a physicist at the National Institute of Standards and Technology and the University of Colorado Boulder, where he develops tools to test foundational issues in quantum mechanics.

MORE TO EXPLORE

Loophole-Free Bell Inequality Violation Using Electron Spins Separated by 1.3 Kilometres. B. Hensen et al. in *Nature,* Vol. 526; pages 682–686; October 29, 2015.

Significant-Loophole-Free Test of Bell's Theorem with Entangled Photons. Marissa Giustina et al. in *Physical Review Letters,* Vol. 115, Article No. 250401. Published online December 16, 2015.

Strong Loophole-Free Test of Local Realism. Lynden K. Shalm et al. in *Physical Review Letters,* Vol. 115, Article No. 250402. Published online December 16, 2015.

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The Un(solv)able Problem

After a years-long intellectual journey, three mathematicians have discovered that a problem of central importance in physics is impossible to solve—and that means other big questions may be undecidable, too

By Toby S. Cubitt, David Pérez-García and Michael M. Wolf

Illustration by Mark Ross Studios

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THE THREE OF US WERE SITTING TOGETHER IN A CAFÉ IN SEEFELD, A SMALL TOWN deep in the Austrian Alps. It was the summer of 2012, and we were stuck. Not stuck in the café—the sun was shining, the snow on the Alps was glistening, and the beautiful surroundings were sorely tempting us to abandon the mathematical problem we were stuck on and head outdoors. We were trying to explore the connections between 20th-century mathematical results by Kurt Gödel and Alan Turing and quantum physics. That, at least, was the dream. A dream that had begun back in 2010, during a semester-long program on quantum information at the Mittag-Leffler Institute near Stockholm.

Some of the questions we were looking into had been explored before by others, but to us this line of research was entirely new, so we were starting with something simple. Just then, we were trying to prove a small and not very significant result to get a feel for things. For months now, we had a proof (of sorts) of this result. But to make the proof work, we had to set up the problem in an artificial and unsatisfying way. It felt like changing the question to suit the answer, and we were not very happy with it. Picking the problem up again during the break after the first session of talks at the workshop in Seefeld that had brought us together in 2012, we still could not see any way around our problems. Half-jokingly, one of us (Michael Wolf) asked, "Why don't we prove the undecidability of something people really care about, like the spectral gap?"

At the time, we were interested in whether certain problems in physics are "decidable" or "undecidable"—that is, can they ever be solved? We had gotten stuck trying to probe the decidability of a much more minor question, one few people care about. The "spectral gap" problem Michael was proposing that we tackle (which we will explain later) was one of central importance to physics. We did not know at the time whether this problem was or was not decidable (although we had a hunch it was not) or whether we would be able to prove it either way. But if we could, the results would be of real relevance to physics, not to mention a substantial mathematical achievement. Michael's ambitious suggestion, tossed off almost as a jest, launched us on a grand adventure. Three years and 146 pages of mathematics later, our proof of the undecidability of the spectral gap was published in *Nature*.

To understand what this means, we need to go back to the beginning of the 20th century and trace some of the threads that gave rise to modern physics, mathematics and computer science. These disparate ideas all lead back to German mathematician David Hilbert, often regarded as the greatest figure of the past 100 years in the field. (Of course, no one outside of mathematics has heard of him. The discipline is not a good route to fame and celebrity, although it has its own rewards.)

THE MATHEMATICS OF QUANTUM MECHANICS

HILBERT'S INFLUENCE on mathematics was immense. Early on, he developed a branch of mathematics called functional analysis—in particular, an area known as spectral theory, which would end up being key to the question within our proof. Hilbert was interested in this area for purely abstract reasons. But as so often happens, his mathematics turned out to be exactly what was necessary to understand a question that was perplexing physicists at the time.

If you heat a substance up, it begins to glow as the atoms in it emit light (hence the phrase "red hot"). The yellow-orange light from sodium street lamps is a good example: sodium atoms predominantly emit light at a wavelength of 590 nanometers, in the yellow part of the visible spectrum. Atoms absorb or release light when electrons within them "jump" between energy levels, and the precise frequency of that light depends on the energy gap between the levels. The frequencies of light emitted by heated materials thus give us a "map" of the gaps between the atom's different energy levels. Explaining these atomic emissions was one of the problems physicists were wrestling with in the first half of the 20th century. The question led directly to the development of quantum mechanics, and the mathematics of Hilbert's spectral theory played a prime role.

One of these gaps between quantum energy levels is especially important. The lowest possible energy level of a material is called its ground state. This is the level it will sit in when it has no heat. To get a material into its ground state, scientists must cool it down

IN BRIEF

Kurt Gödel famously discovered in the 1930s that some statements are impossible to prove true or false—they will always be "undecidable." **Mathematicians recently** set out to discover whether a certain fundamental problem in quantum physics—the so-called spectral gap question—falls into this category. The spectral gap refers to the energy difference between the lowest energy state a material can occupy and the next state up. **After three years** of blackboard brainstorming, midnight calculating and much theorizing over coffee, the mathematicians produced a 146-page proof that the spectral gap problem is, in fact, undecidable. The result raises the possibility that other important questions may likewise be unanswerable.

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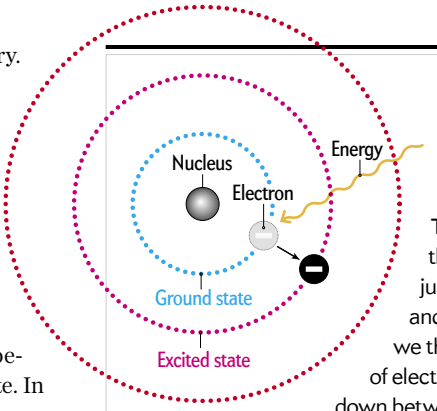
to extremely low temperatures in a laboratory. Then, if the material is to do anything other than sit in its ground state, something must excite it to a higher energy. The easiest way is for it to absorb the smallest amount of energy it can, just enough to take it to the next energy level above the ground state—the first excited state. The energy gap between the ground state and this first excited state is so critical that it is often just called the spectral gap.

In some materials, there is a large gap between the ground state and the first excited state. In other materials, the energy levels extend all the way down to the ground state without any gaps at all. Whether a material is "gapped" or "gapless" has profound consequences for its behavior at low temperatures. It plays a particularly significant role in quantum phase transitions.

A phase transition happens when a material undergoes a sudden and dramatic change in its properties. We are all very familiar with some phase transitions—such as water transforming from its solid form of ice into its liquid form when heated up. But there are more exotic quantum phase transitions that happen even when the temperature is kept extremely low. For example, changing the magnetic field around a material or the pressure it is subjected to can cause an insulator to become a superconductor or cause a solid to become a superfluid.

How can a material go through a phase transition at a temperature of absolute zero (−273.15 degrees Celsius), at which there is no heat at all to provide energy? It comes down to the spectral gap. When the spectral gap disappears—when a material is gapless—the energy needed to reach an excited state becomes zero. The tiniest amount of energy will be enough to push the material through a phase transition. In fact, thanks to the weird quantum effects that dominate physics at these very low temperatures, the material can temporarily "borrow" this energy from nowhere, go through a phase transition and "give" the energy back. Therefore, to understand quantum phase transitions and quantum phases, we need to determine when materials are gapped and when they are gapless.

Because this spectral gap problem is so fundamental to understanding quantum phases of matter, it crops up all over the place in theoretical physics. Many famous and long-standing open problems in condensed matter physics boil down to solving this problem for a specific material. A closely related question even crops up in particle physics: there is very good evidence that the fundamental equations describing quarks and their interactions have a "mass gap." Experimental data from particle colliders such as the Large Hadron Collider near Geneva support this notion, as do massive number-crunching results from supercomputers. But proving the idea rigorously from the theory seems to be extremely difficult. So difficult, in fact, that this problem, called the Yang-Mills mass gap problem, has been named one of seven Millennium Prize problems by the Clay Mathematics Institute, and anyone who solves it is entitled to a $1-million prize. All these problems are particular cases of the general spectral gap question. We have bad news for anyone trying to solve them, though. Our proof shows that the general problem is even trickier than we thought. The reason comes down to a question called the *Entscheidungsproblem*.

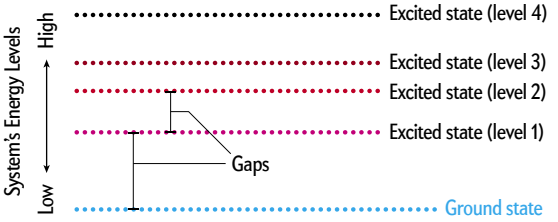


The Spectral Gap

The authors' mathematical proof took on the question of the "spectral gap"—the jump in energy between the ground state and first excited state of a material. When we think of energy states, we tend to think of electrons in atoms, which can jump up and down between energy levels. Whereas in atoms there is always a gap between such levels, in larger materials made of many atoms, there is sometimes no distance between the ground state and the first excited state: even the smallest possible amount of energy will be enough to push the material up an energy level. Such materials are called "gapless." The authors proved that it will never be possible to determine whether all materials are gapped or gapless.

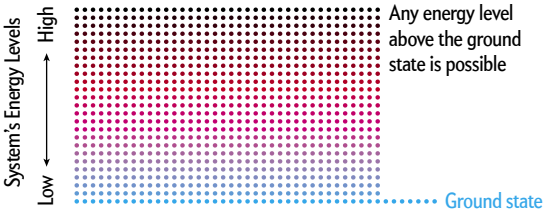
Gapped System

There are discrete gaps between each energy level, and the material must reach a certain energy to make the leap to the next level.



Gapless System

No expanse separates the ground state and first excited state, and the material may become excited with just the tiniest input of energy.



UNANSWERABLE QUESTIONS

BY THE 1920S Hilbert had become concerned with putting the foundations of mathematics on a firm, rigorous footing—an endeavor that became known as Hilbert's program. He believed

Illustration by Jen Christiansen

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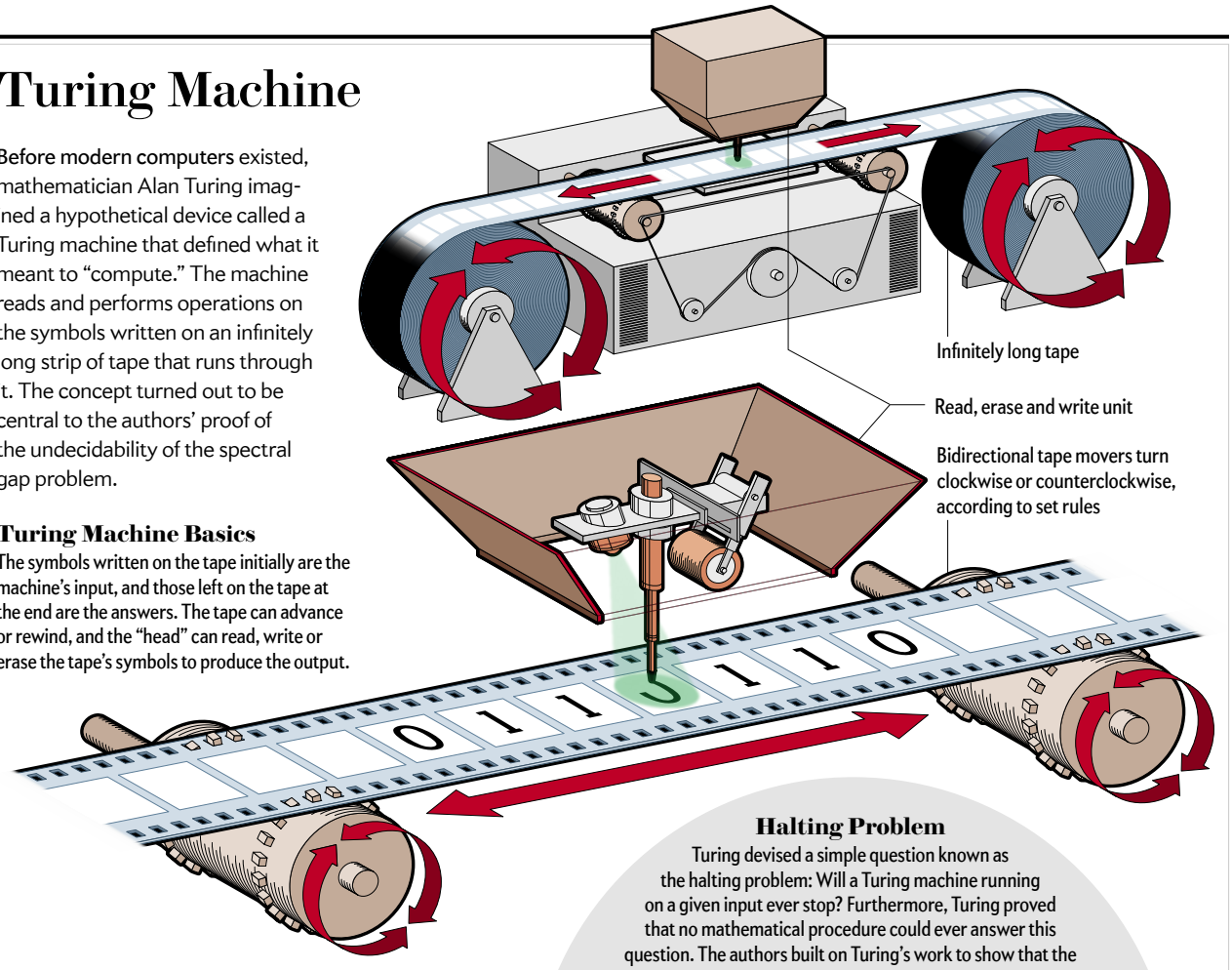
Turing Machine

Before modern computers existed, mathematician Alan Turing imagined a hypothetical device called a Turing machine that defined what it meant to "compute." The machine reads and performs operations on the symbols written on an infinitely long strip of tape that runs through it. The concept turned out to be central to the authors' proof of the undecidability of the spectral gap problem.

Turing Machine Basics

The symbols written on the tape initially are the machine's input, and those left on the tape at the end are the answers. The tape can advance or rewind, and the "head" can read, write or erase the tape's symbols to produce the output.


Infinitely long tape
Read, erase and write unit
Bidirectional tape movers turn clockwise or counterclockwise, according to set rules
0 1 1 1 1 1 0

Halting Problem

Turing devised a simple question known as the halting problem: Will a Turing machine running on a given input ever stop? Furthermore, Turing proved that no mathematical procedure could ever answer this question. The authors built on Turing's work to show that the spectral gap is similar to the halting problem and is likewise undecidable.

that whatever mathematical conjecture one might make, it will in principle be possible to prove either that it is true or that it is false. (It had better not be possible to prove that it is both, or something has gone very wrong with mathematics!) This idea might seem obvious, but mathematics is about establishing concepts with absolute certainty. Hilbert wanted a rigorous proof.

In 1928 he formulated the *Entscheidungsproblem*. Although it sounds like the German sound for a sneeze, in English it translates to "the decision problem." It asks whether there is a procedure, or "algorithm," that can decide whether mathematical statements are true or false.

For example, the statement "Multiplying any whole number by 2 gives an even number" can easily be proved true, using basic logic and arithmetic. Other statements are less clear. What about the following example? "If you take any whole number, and repeatedly multiply it by 3 and add 1 if it's odd or divide it by 2 if it's even, you always eventually reach the number 1." (Have a think about it.)

Unfortunately for Hilbert, his hopes were to be dashed. In 1931 Gödel published some remarkable results now known as his incompleteness theorems. Gödel showed that there are perfectly reasonable mathematical statements about whole numbers that can be neither proved nor disproved. In a sense, these statements are beyond the reach of logic and arithmetic. And he proved this assertion. If that is hard to wrap your head around, you are in good company. Gödel's incompleteness theorems shook the foundations of mathematics to the core.

Here is a flavor of Gödel's idea: If someone tells you, "This sentence is a lie," is that person telling the truth or lying? If he or she is telling the truth, then the statement must indeed be a lie. But if he or she is lying, then it is true. This quandary is known as the liar paradox. Even though it appears to be a perfectly reasonable English sentence, there is no way to determine whether it is true or false. What Gödel managed to do was to construct a rigorous mathematical version of the liar paradox using only basic arithmetic.

The next major player in the story of the *Entscheidungsproblem* is Alan Turing, the English computer scientist. Turing is most famous among the general public for his role in breaking the German Enigma code during World War II. But among scientists, he is best known for his 1937 paper "On Computable Numbers, with an Application to the *Entscheidungsproblem*." Strongly influenced by Gödel's result, the young Turing had given a negative answer to Hilbert's *Entscheidungsproblem* by proving that no general algorithm to decide whether mathematical statements are true or false can exist. (American mathema-

Illustration by Ben Gilliland

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tician Alonzo Church also independently proved this just before Turing. But Turing's proof was ultimately more significant. Often in mathematics, the proof of a result turns out to be more important than the result itself.)

To solve the *Entscheidungsproblem,* Turing had to pin down precisely what it meant to "compute" something. Nowadays we think of computers as electronic devices that sit on our desk, on our lap or even in our pocket. But computers as we know them did not exist in 1936. In fact, "computer" originally meant a person who carried out calculations with pen and paper. Nevertheless, computing with pen and paper as you did in high school is mathematically no different to computing with a modern desktop computer—just much slower and far more prone to mistakes.

Turing came up with an idealized, imaginary computer called a Turing machine. This very simple imaginary machine does not look like a modern computer, but it can compute everything that the most powerful modern computer can. In fact, any question that can ever be computed (even on quantum computers or computers from the 31st century that have yet to be invented) could also be computed on a Turing machine. It would just take the Turing machine much longer.

A Turing machine has an infinitely long ribbon of tape and a "head" that can read and write one symbol at a time on the tape, then move one step to the right or left along it. The input to the computation is whatever symbols are originally written on the tape, and the output is whatever is left written on it when the Turing machine finally stops running (halts). The invention of the Turing machine was more important even than the solution to the *Entscheidungsproblem*. By giving a precise, mathematically rigorous formulation of what it meant to make a computation, Turing founded the modern field of computer science.

Having constructed his imaginary mathematical model of a computer, Turing then went on to prove that there is a simple question about Turing machines that no mathematical procedure can ever decide: Will a Turing machine running on a given input ever halt? This question is known as the halting problem. At the time, this result was shocking. Mathematicians have become accustomed to the fact that any conjecture we are working on could be provable, disprovable or undecidable.

WHERE WE COME IN

IN OUR RESULT, we had to tie all these disparate threads back together. We wanted to unite the quantum mechanics of the spectral gap, the computer science of undecidability and Hilbert's spectral theory to prove that—like the halting problem—the spectral gap problem was one of the undecidable ones that Gödel and Turing taught us about.

Chatting in that café in Seefeld in 2012, we had an idea for how we might be able to prove a weaker mathematical result related to the spectral gap. We tossed this idea around, not even scribbling on the back of a napkin, and it seemed like it might work. Then the next session of talks started. And there we left it.

A few months later one of us (Toby Cubitt) visited Michael in Munich, and we did what we had not done in Seefeld: jotted some equations down on a scrap of paper and convinced ourselves the idea worked. In the following weeks, we completed the argument and wrote it up properly in a private four-page note. (Nothing in mathematics is truly proved until you write it down—or, better still, type it up and show it to a colleague for scrutiny.) Conceptually this was a major advance. Before now, the idea of proving the undecidability of the spectral gap was more of a joke than a serious prospect. Now we had the first glimmerings that it might actually be possible. But there was still a very long way to go. We could not extend our initial idea to prove the undecidability of the spectral gap problem itself.

BURNING THE MIDNIGHT COFFEE

WE ATTEMPTED to make the next leap by linking the spectral gap problem to quantum computing. In 1985 Nobel Prize–winning physicist Richard Feynman published one of the papers that launched the idea of quantum computers. In that paper, Feynman showed how to relate ground states of quantum systems to computation. Computation is a dynamic process: you supply the computer with input, and it goes through several steps to compute a result and outputs the answer. But ground states of quantum systems are completely static: the ground state is just the configuration a material sits in at zero temperature, doing nothing at all. So how can it make a computation?

The answer comes through one of the defining features of quantum mechanics: superposition, which is the ability of objects to occupy many states simultaneously, as, for instance, Erwin Schrödinger's famous quantum cat can be alive and dead at the same time. Feynman proposed constructing a quantum state that is in a superposition of the various steps in a computation—initial input, every intermediate step of the computation and final output—all at once. Alexei Kitaev of the California Institute of Technology later developed this idea substantially by constructing an imaginary quantum material whose ground state looks exactly like this.

If we used Kitaev's construction to put the entire history of a Turing machine into the material's ground state in superposition, could we transform the halting problem into the spectral gap problem? In other words, could we show that any method for solving the spectral gap problem would also solve the halting problem? Because Turing had already shown that the halting problem was undecidable, this would prove that the spectral gap problem must also be undecidable.

Encoding the halting problem in a quantum state was not a new idea. Seth Lloyd, now at the Massachusetts Institute of Technology, had proposed this almost two decades earlier to show the undecidability of another quantum question. Daniel Gottesman of the Perimeter Institute for Theoretical Physics in Waterloo and Sandy Irani of the University of California, Irvine, had used Kitaev's idea to prove that even single lines of interacting quantum particles can show very complex behavior. In fact, it was Gottesman and Irani's version of Kitaev's construction that we hoped to make use of.

But the spectral gap is a different kind of problem, and we faced some apparently insurmountable mathematical obstacles. The first had to do with supplying the input into the Turing machine. Remember that the undecidability of the halting problem is about whether the Turing machine halts *on a given input.* How could we design our imaginary quantum material in a way that would let us choose the input to the Turing machine to be encoded in the ground state?

When working on that earlier problem (the one we were still

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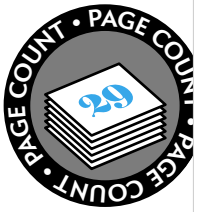
stuck on in the café in Seefeld), we had an idea of how to rectify the issue by putting a "twist" in the interactions between the particles and using the angle of this rotation to create an input to the Turing machine. In January 2013 we met at a conference in Beijing and discussed this plan together. But we quickly realized that what we had to prove came very close to contradicting known results about quantum Turing machines. We decided we needed a complete and rigorous proof that our idea worked before we pursued the project further.

At this point, Toby had been part of David Pérez-García's group at Complutense University of Madrid for more than two years. In that same month he moved to the University of Cambridge, but his new apartment there was not yet ready, so his friend and fellow quantum information theorist Ashley Montanaro offered to put him up. For those two months, he set to work producing a rigorous proof of this idea. His friend would find him at the kitchen table in the morning, a row of empty coffee mugs next to him, about to head to bed, having worked through the night figuring out details and typing them up. At the end of those two months, Toby sent around the completed proof.



IN REMEMBRANCE OF TILINGS PAST

THIS 29-PAGE PROOF showed how to overcome one of the obstacles to connecting the ground state of a quantum material to computation with a Turing machine. But there was an even bigger obstacle to that goal: the resulting quantum material was always gapless. If it is always gapless, the spectral gap problem for this particular material is very easy to solve: the answer is gapless!

Our first idea from Seefeld, which proved a much weaker result than we wanted, nonetheless managed to get around this obstacle. The key was using "tilings." Imagine you are covering a large bathroom floor with tiles. In fact, imagine it is an infinitely big bathroom. The tiles have a very simple pattern on them: each of the four sides of the tile is a different color. You have various boxes of tiles, each with a different arrangement of colors. Now imagine there is an infinite supply of tiles in each box. You, of course, want to tile the infinite bathroom floor so that the colors on adjacent tiles match. Is this possible?

The answer depends on which boxes of tiles you have available. With some sets of colored tiles, you will be able to tile the infinite bathroom floor. With others, you will not. Before you select which boxes of tiles to buy, you would like to know whether or not they will work. Unfortunately for you, in 1966 mathematician Robert Berger proved that this problem is undecidable.

One easy way to tile the infinite bathroom floor would be to first tile a small rectangle so that colors on opposite sides of it match. You could then cover the entire floor by repeating this rectangular pattern. Because they repeat every few tiles, such patterns are called periodic. The reason the tiling problem is undecidable is that nonperiodic tilings also exist: patterns that cover the infinite floor but never repeat.

Back when we were discussing our first small result, we studied a 1971 simplification of Berger's original proof made

Tiling an Infinite Bathroom Floor

To connect the spectral gap problem to the halting problem, the authors considered the classic mathematical question of how to tile an infinitely large floor. Imagine you have a box with a certain selection of tiles, and you want to arrange them so that the colors on the sides of each tile match those next to them. In some cases, this is possible by tiling the floor in either a repeating "periodic" pattern or a fractal-like "aperiodic" pattern.

Periodic Tiles

One version of the classic problem concerns tiles that come in three varieties containing five different colors. In this particular case, it is possible to tile the floor with all sides matching up by creating a rectangle that repeats. On each side of the rectangle, the colors match so that many versions of the same rectangle can be placed next to one another in an infinite pattern.

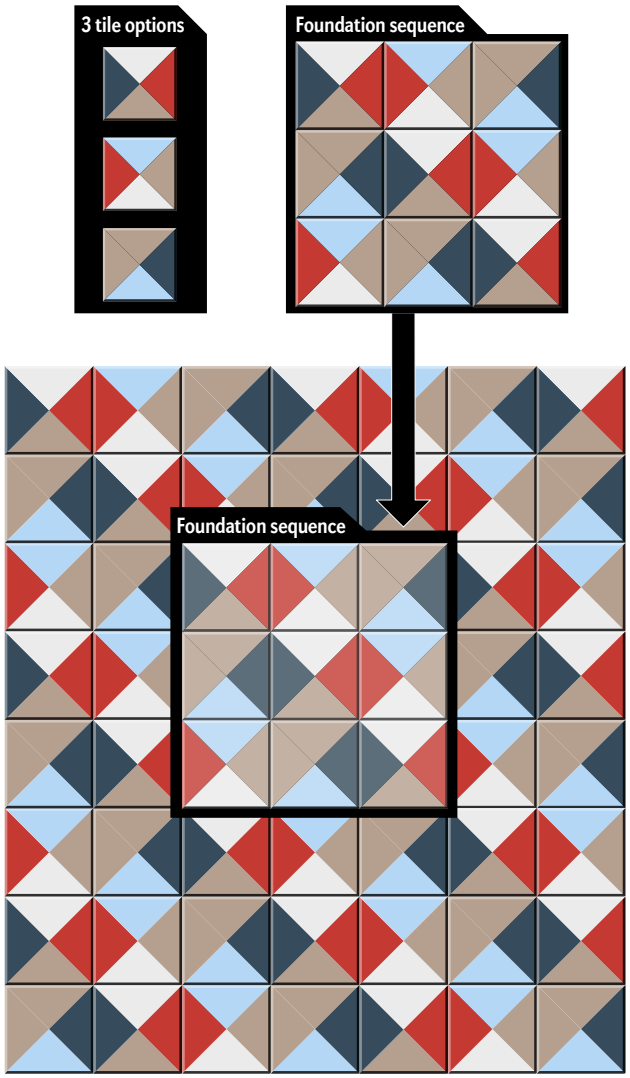


Illustration by Jen Christiansen

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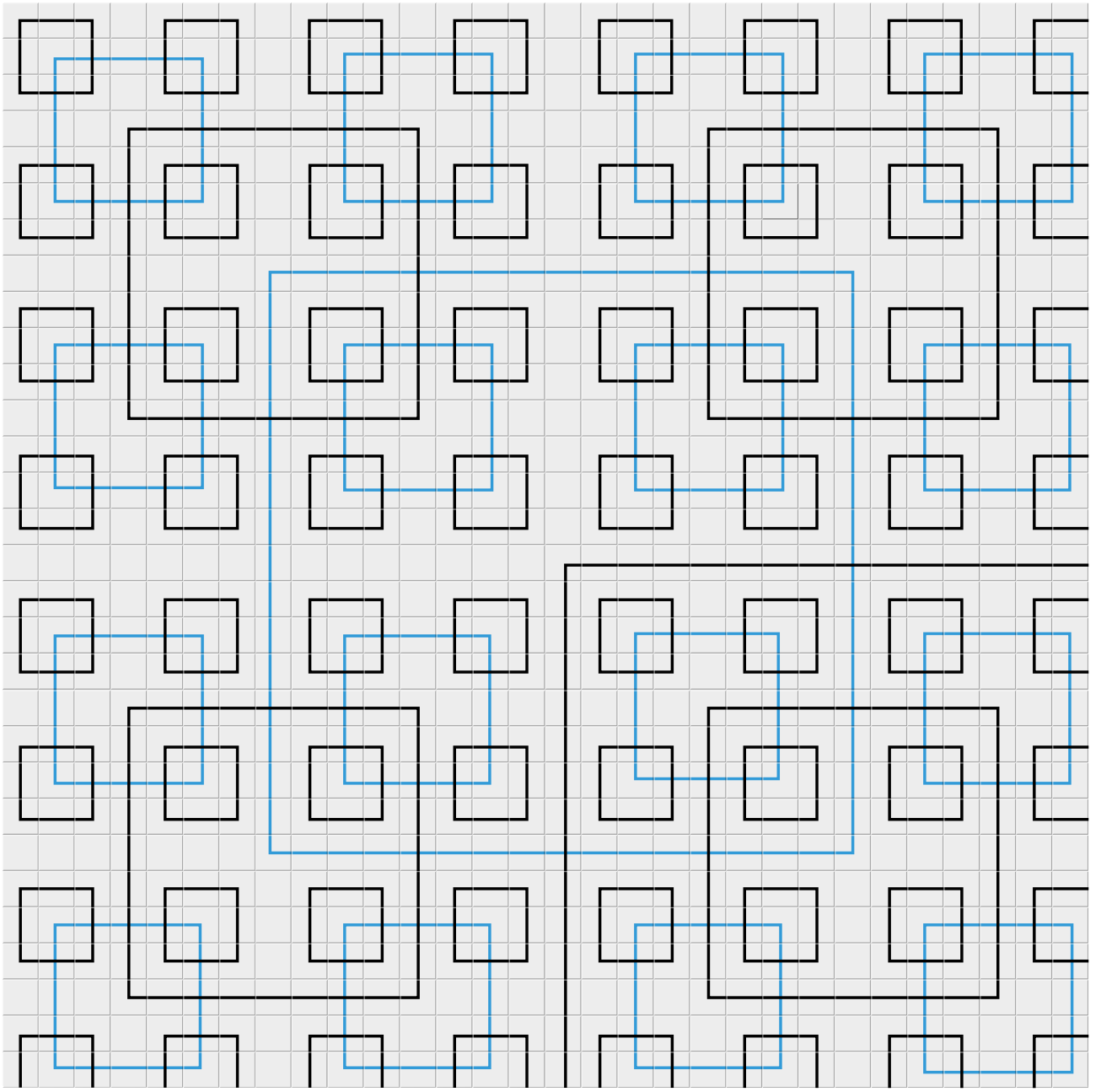
Aperiodic Tiles

In their proof, the authors used a particular set of tiles designed by mathematician Rafael Robinson in 1971. Robinson's tiles fit together in an ever expanding sequence that does not quite repeat but instead creates a fractal-like pattern. All rotations of the six tiles shown here are allowed. There are also other ways to fit these pieces together in a periodic pattern, but by adding more markings to these tiles (*not shown*), Robinson designed a set of 56 tiles for which no pattern is possible other than the one shown.



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by Rafael Robinson of the University of California, Berkeley. Robinson constructed a set of 56 different boxes of tiles that, when used to tile the floor, produce an interlocking pattern of ever larger squares. This fractal pattern looks periodic, but in fact, it never quite repeats itself. We extensively discussed ways of using tiling results to prove the undecidability of quantum properties. But back then, we were not even thinking about the spectral gap. The idea lay dormant.

In April 2013 Toby paid a visit to Charlie Bennett at IBM's Thomas J. Watson Research Center. Among Bennett's many achievements before becoming one of the founding fathers of quantum information theory was his seminal 1970s work on Turing machines. We wanted to quiz him about some technical details of our proof to make sure we were not overlooking something. He said he had not thought about this stuff for 40 years, and it was high time a younger generation took over. (He then went on to very helpfully explain some subtle mathematical details of his 1970s work, which reassured us that our proof was okay.)

Bennett has an immense store of scientific knowledge. Because we had been talking about Turing machines and undecidability, he e-mailed copies of a couple of old papers on undecidability he thought might interest us. One of these was the same 1971 paper by Robinson that we had studied. Now the time was right for the ideas sowed in our earlier discussions to spring to life. Reading Robinson's paper again, we realized it was exactly what we needed to prevent the spectral gap from vanishing.

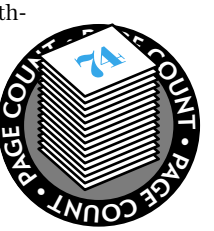
Our initial idea had been to encode one copy of the Turing machine into the ground state. By carefully designing the interactions between the particles, we could make the ground state energy a bit higher if the Turing machine halted. The spectral gap—the energy jump to the first excited state—would then depend on whether the Turing machine halted or not. There was just one problem with this idea, and it was a big one. As the number of particles increased, the additional contribution to the ground state energy got closer and closer to zero, leading to a material that was always gapless.

But by adapting Berger's tiling construction, we could instead encode *many copies* of exactly the same Turing machine into the ground state. In fact, we could attach one copy to each square in Robinson's tiling pattern. Because these are identical copies of the same Turing machine, if one of them halts, they all halt. The energy contributions from all these copies add up. As the number of particles increases, the number of squares in the tiling pattern gets bigger. Thus, the number of copies of the Turing machine increases, and their energy contribution becomes huge, giving us the possibility of a spectral gap.

EXAMS AND DEADLINES

ONE SIGNIFICANT WEAKNESS remained in the result we had proved. We could not say anything about how *big* the energy gap was when the material was gapped. This uncertainty left our result open to the criticism that the gap could be so small that it might as well not exist. We needed to prove that the gap, when it existed, was actually large. The first solution we found arose by considering materials in three dimensions instead of the planar materials we had been thinking about until then.

When you cannot stop thinking about a mathematical problem, you make progress in the most unexpected places. David worked on the details of this idea in his head while he was supervising an exam. Walking along the rows of tables in the hall, he was totally oblivious to the students working feverishly around him. Once the test was over, he committed this part of the proof to paper.



We now knew that getting a big spectral gap was possible. Could we also get it in two dimensions, or were three necessary? Remember the problem of tiling an infinite bathroom floor. What we needed to show was that for the Robinson tiling, if you got one tile wrong somewhere, but the colors still matched everywhere else, then the pattern formed by the tiles would be disrupted only in a small region centered on that wrong tile. If we could show this "robustness" of the Robinson tiling, it would imply that there was no way of getting a small spectral gap by breaking the tiling only a tiny bit.

By the late summer of 2013, we felt we had all the ingredients for our proof to work. But there were still some big details to be resolved, such as proving that the tiling robustness could be merged with all the other proof ingredients to give the complete result. The Isaac Newton Institute for Mathematical Science in Cambridge, England, was hosting a special workshop on quantum information for the whole of the autumn semester of 2013. All three of us were invited to attend. It was the perfect opportunity to work together on finishing the project. But David was not able to stay in Cambridge for long. We were determined to complete the proof before he left.

The Isaac Newton Institute has blackboards everywhere—even in the bathrooms! We chose one of the blackboards in a corridor (the closest to the coffee machine) for our discussions. We spent long hours at the blackboard developing the missing ideas, then divided the task of making these ideas mathematically rigorous among us. This process always takes far more time and effort than it seems on the blackboard. As the date of David's departure loomed, we worked without interruption all day and most of the night. Just a few hours before he left for home, we finally had a complete proof.

In physics and mathematics, researchers make most results public for the first time by posting a draft paper to the arXiv.org preprint server before submitting it to a journal for peer review. Although we were now fairly confident the entire argument worked and the hardest part was behind us, our proof was not ready to be posted. There were many mathematical details to be filled in. We also wanted to rewrite and tidy up the paper (we hoped to reduce the page count in the process, although in this we would completely fail). Most important, although at least one of us had checked every part of the proof, no one had gone through it all from beginning to end.

In summer 2014 David was on a sabbatical at the Technical University of Munich with Michael. Toby went out to join them. The plan was to spend this time checking and completing the whole proof, line by line. David and Toby were sharing an office. Each morning David would arrive with a new printout of the

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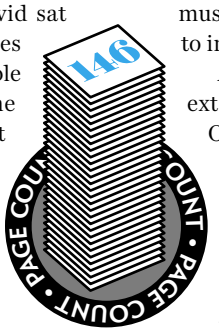
draft paper, copious notes and questions scribbled in the margins and on interleaved sheets. The three of us would get coffee and then pick up where we had left off the day before, discussing the next section of the proof at the blackboard. In the afternoon, we divided up the work of rewriting the paper and adding the new material and of going through the next section of the proof. Toby was suffering from a slipped disc and could not sit down, so he worked with his laptop propped on top of an upturned garbage bin on top of the desk. David sat opposite, the growing pile of printouts and notes taking up more and more of his desk. On a couple of occasions, we found significant gaps in the proof. These turned out to be surmountable, but bridging them meant adding substantial material to it. The page count continued to grow.



After six weeks, we had checked, completed and improved every single line of the proof. It would take another six months to finish writing everything up. Finally, in February 2015, we uploaded the paper to arXiv.org.

WHAT IT ALL MEANS

ULTIMATELY what do these 146 pages of complicated mathematics tell us?

First, and most important, they give a rigorous mathematical proof that one of the basic questions of quantum physics cannot be solved in general. Note that the "in general" here is critical. Even though the halting problem is undecidable in general, for *particular* inputs to a Turing machine, it is often still possible to say whether it will halt or not. For example, if the first instruction of the input is "halt," the answer is pretty clear. The same goes if the first instruction tells the Turing machine to loop forever. Thus, although undecidability implies that the spectral gap problem cannot be solved for *all* materials, it is entirely possible to solve it for specific materials. In fact, condensed matter physics is littered with such examples. Nevertheless, our result proves rigorously that even a perfect, complete description of the microscopic interactions between a material's particles is not always enough to deduce its macroscopic properties.

You may be asking yourself if this finding has any implications for "real physics." After all, scientists can always try to measure the spectral gap in experiments. Imagine if we could engineer the quantum material from our mathematical proof and produce a piece of it in the lab. Its interactions are so extraordinarily complicated that this task is far, far beyond anything scientists are ever likely to be able to do. But if we could and then took a piece of it and tried to measure its spectral gap, the material could not simply throw up its hands and say, "I can't tell you—it's undecidable." The experiment would have to measure *something*.

The answer to this apparent paradox lies in the fact that, strictly speaking, the terms "gapped" and "gapless" only make mathematical sense when the piece of material is infinitely large. Now, the 10^{23} or so atoms contained in even a very small piece of material represent a very large number indeed. For normal materials, this is close enough to infinity to make no difference. But for the very strange material constructed in our proof, large is not equivalent to infinite. Perhaps with 10^{23} atoms, the material appears in experiments to be gapless. Just to be sure, you take a sample of material twice the size and measure again. Still gapless. Then, late one night, your graduate student comes into the lab and adds just one extra atom. The next morning, when you measure it again, the material has become gapped! Our result proves that the size at which this transition may occur is incomputable (in the same Gödel-Turing sense that you are now familiar with). This story is completely hypothetical for now because we cannot engineer a material this complex. But it shows, backed by a rigorous mathematical proof, that scientists must take special care when extrapolating experimental results to infer the behavior of the same material at larger sizes.

After the work described here was complete, we went on to extend it to one-dimensional systems and phase diagrams. Other important problems in quantum physics have since been shown to be undecidable using techniques from computer science, with profound consequences for mathematics. In 1935 Einstein, Podolsky and Rosen realized that quantum mechanics predicted what they called "spooky action at distance"—correlations between pairs of entangled quantum particles that are not possible under classical physics. In a major breakthrough, a team led by Zhengfeng Ji of the University of Technology Sydney recently announced a result proving that estimating such correlations, even to within some reasonable precision, is undecidable in general. Their result disproves a deep conjecture in mathematics that had been open for more than 40 years.

And now we come back to the Yang-Mills problem—the question of whether the equations describing quarks and their interactions have a mass gap. Computer simulations indicate that the answer is yes, but our result suggests that determining for sure may be another matter. Could it be that the computer-simulation evidence for the Yang-Mills mass gap would vanish if we made the simulation just a tiny bit larger? Our result cannot say, but it does open the door to the intriguing possibility that the Yang-Mills problem, and other problems important to physicists, may be undecidable.

And what of that original small and not very significant result we were trying to prove all those years ago in a café in the Austrian Alps? Actually, we are still working on it. SA

Toby S. Cubitt is a Royal Society University Research Fellow and reader in quantum information at University College London. After a Ph.D. in physics, postdoctoral positions in mathematics and a faculty position in computer science, he now works on quantum problems that straddle these areas.

David Pérez-García is a professor of mathematics at Complutense University of Madrid and a faculty member at the Institute of Mathematical Sciences in Madrid. He works on mathematical problems in quantum physics.

Michael M. Wolf is a professor of mathematical physics in the department of mathematics at the Technical University of Munich. His research focuses on the mathematical and conceptual foundations of quantum theory.

MORE TO EXPLORE

Undecidability and Nonperiodicity for Tilings of the Plane. Raphael M. Robinson in *Inventiones Mathematicae,* Vol. 12, No. 3, pages 177–209; September 1971.

Undecidability of the Spectral Gap. Toby S. Cubitt, David Pérez-García and Michael M. Wolf in *Nature,* Vol. 528, pages 207–211; December 10, 2015. Preprint available at https://arxiv.org/abs/1502.04573

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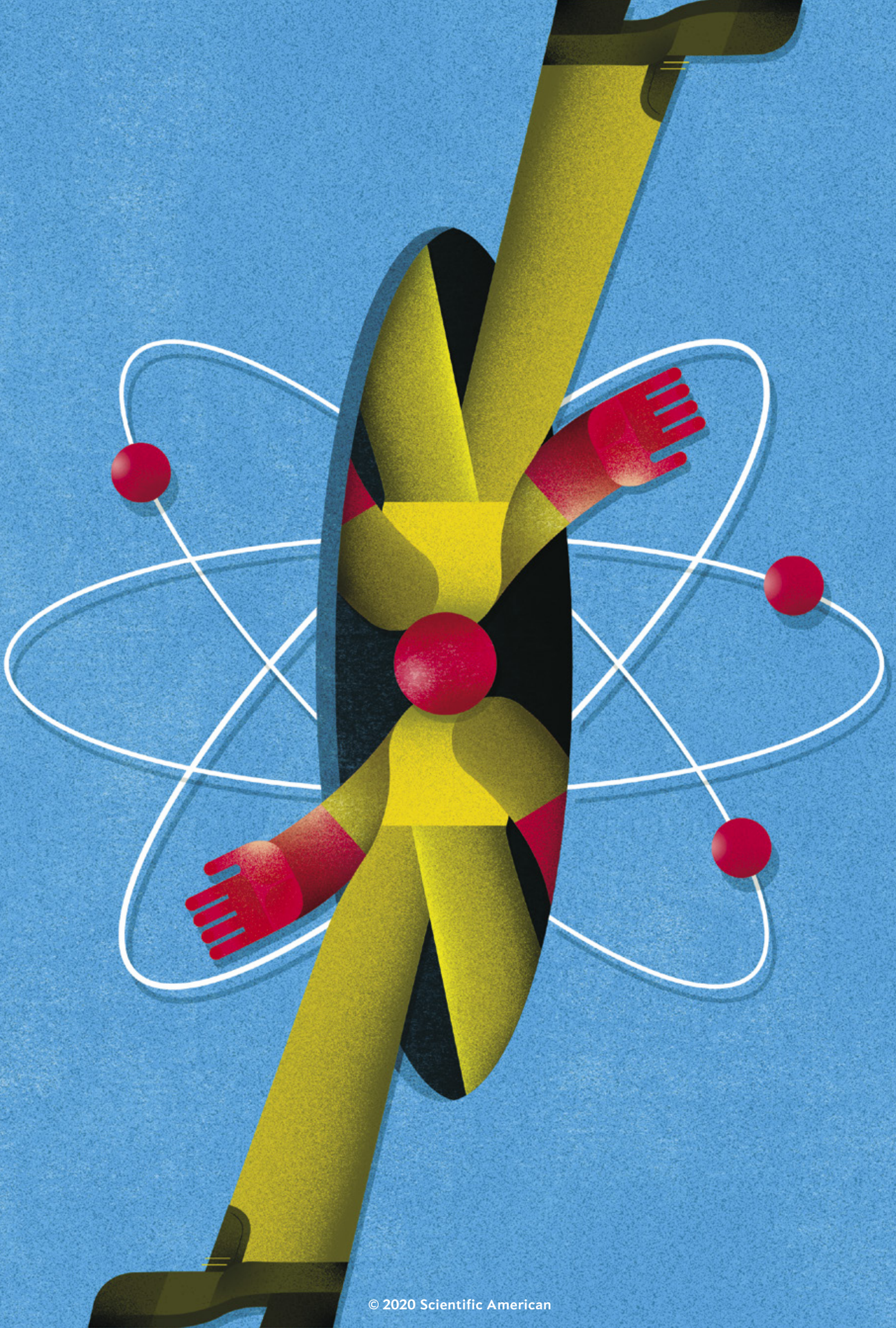

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CROSSING THE QUANTUM DIVIDE

The universe according to quantum mechanics is strange and probabilistic, but our everyday reality seems nailed down. New experiments aim to probe where—and why—one realm passes into the other

By Tim Folger

Illustration by Maria Corte

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MOST OF SIMON GRÖBLACHER'S HANDIWORK IS INVISIBLE TO THE NAKED EYE. One of the mechanical devices he fashioned in his laboratory at the Delft University of Technology in the Netherlands is just a few millionths of a meter long—not much bigger than a bacterium—and 250 nanometers thick—about a thousandth of the thickness of a sheet of paper. Gröblacher no doubt could continue to shrink his designs, but he has a different goal: he wants to scale things *up,* not down. "What we're trying to do is make things that are really, really big," he says as he brings up images of hardware on his computer. Keep in mind that for Gröblacher, an experimental physicist, "really, really big" means something just barely visible without a microscope, "a millimeter by a millimeter in size."

IN BRIEF

The microscopic and macroscopic worlds do not blend seamlessly: the probabilistic nature of quantum mechanics reigns over the first, whereas the second observes more logical "classical" rules.

Physicists have long been stymied over the question of where one realm ends and the other begins, but upcoming experiments offer hope of testing different theories.

One possibility, called continuous spontaneous localization (CSL), suggests that quantum probabilities randomly collapse into classical certainties. If true, these collapses would also create a sea of background vibrations in the universe that experiments could detect.

By working on that less than humongous scale, Gröblacher hopes to address an extraordinary question: Can a single macroscopic object be in two places at once? Could something the size of a pinhead, say, exist both here and there at the same time? That seemingly impossible condition is actually the norm for atoms, photons and all other particles. According to the surreal laws of quantum theory, reality at its most basic level defies our commonsense assumptions: Particles do not have fixed positions, energies or any other definite properties—at least while no one is looking. They exist in numerous states simultaneously.

But for reasons physicists do not understand, the reality we see is different. Our world—even the parts we cannot observe directly—appears to be distinctly *un*quantum. Really big things—meaning anything from a virus on up—always manifest in one place and one place only; there is just one Gröblacher talking to one jet-lagged, scribbling journalist in his Delft lab. And therein lies a mystery: Why, if everything is built on a quantum blur of matter and energy, do we not experience quantum weirdness ourselves? Where does the quantum world end and the so-called classical world of Newtonian physics begin? Is there a rift in reality, a scale beyond which quantum effects simply cease? Or does quantum mechanics reign everywhere, and we are somehow blind to it?

"We know the microworld is quantum, and we know in one way or another, we are classical—whatever that means," says Angelo Bassi, a theoretical physicist at the University of Trieste in Italy. "We are ignorant about the true nature of matter in between the micro and the macro." That no-man's-land has baffled physicists since the birth of quantum theory a century ago. But in recent years Gröblacher and other physicists have started running exquisitely sensitive tabletop experiments that may one day reveal how objects make the startling transition from quantum to quotidian. Whether those efforts will resolve the mysteries of quantum theory or deepen them, no one can yet say. But in probing the wild and woolly quantum borderlands, researchers stand a chance of discovering a whole new realm of physics.

THE MEASUREMENT PROBLEM

FOR ALL ITS PARADOXES, quantum mechanics is the most powerful and exacting scientific theory ever devised. The theory's predictions match experiment with ridiculous precision—to better than parts-per-trillion accuracy in some cases. By revolutionizing our understanding of atomic structure, it transformed every facet of science, from biology to astrophysics. Without quantum theory, there would be no electronics industry, no cell phones, no Google. Yet the theory has one glaring shortcoming, says Stephen L. Adler, a theoretical physicist at the Institute for Advanced Study in Princeton, N.J.: "In quantum mechanics, things don't happen."

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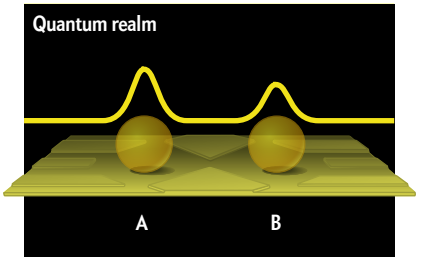
Separate Realms

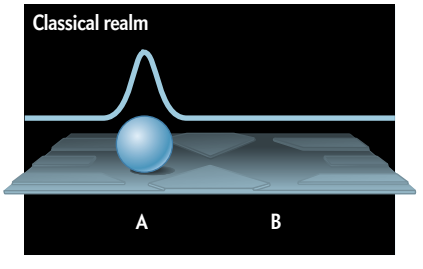
Quantum mechanics produces some bizarre effects in the microscopic world, but we do not see these phenomena in our macroscopic, "classical" reality. Why is that? Scientists have never understood why and how the universe crosses over between these realms, but several theories, as depicted here, offer possible explanations.

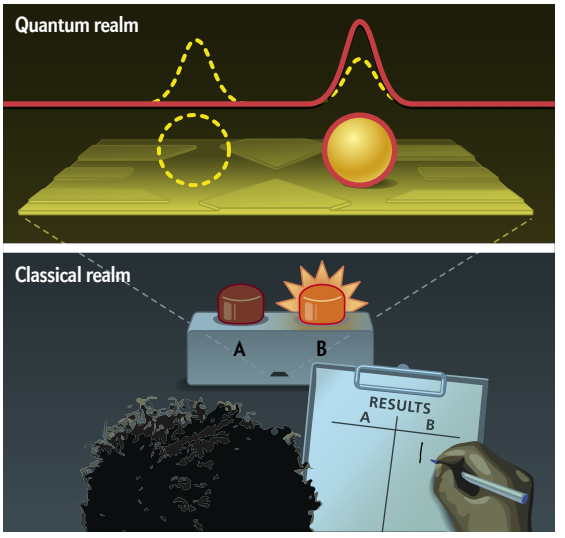
Quantum vs. Classical

According to quantum mechanics, particles do not exist in definite states—here or there, having this energy or that—but rather take on all possible states and positions. The theory describes particles with equations called wave functions, which are combinations, or "superpositions," of multiple waves. The amplitude of each peak in a wave function denotes the probability of a particle being found in any specific circumstances—for instance, at point A or B, as shown.



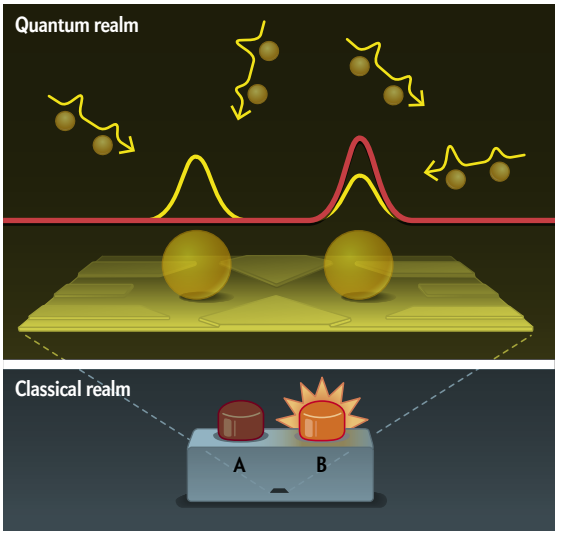
Strangely, when scientists make a measurement of a particle, this act appears to reduce all the quantum possibilities to one, seemingly chosen at random. The experiment will find the particle at point A, for example, and the particle enters the classical realm, ceasing to be in a superposition.





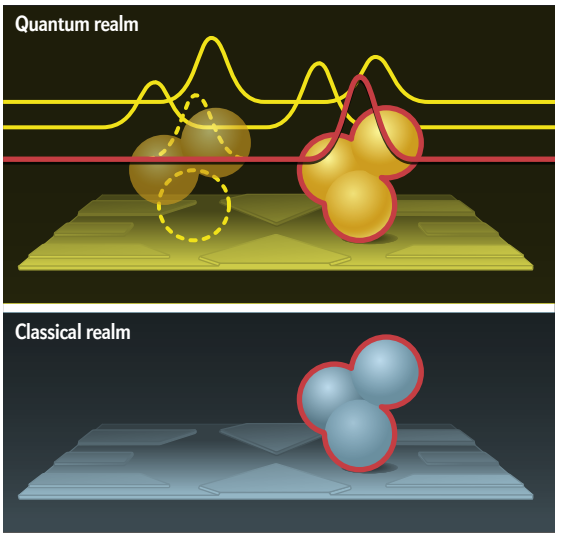
Collapse at Measurement

One theory for how the universe crosses over from quantum to classical is that the act of measurement intervenes. Particles can linger in quantum superpositions (*dotted yellow lines*) as long as no one looks too closely, but once humans make a measurement, the particle is forced to "choose" a specific state (*solid red lines*). How this happens, and why human measurement should take on such a significance in physics, remains mystifying.



Decoherence

Another theory posits that a particle's environment is to blame for moving it from the quantum world to the classical. As long as a particle is undisturbed by any outside influence, so the thinking goes, it can remain in superposition. But when the wave functions of other particles or objects nearby meet with its own, they interfere, causing the particle's many quantum possibilities to "collapse" into a single classical reality.



Continuous Spontaneous Localization

Another possibility is that the collapse of the wave function to a single possibility is a random event, not caused by human or environmental interference. The chances of any one particle collapsing at any given time are extremely small, but in macroscopic objects containing multitudes of atoms, the collapse of at least one is inevitable, which then causes the entire structure to collapse.

Illustrations by Jen Christiansen

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Adler's cryptic comment refers to what the basic equations of quantum theory say—or do not say—about the nature of reality. Known as wave functions, the equations assign probabilities to an object's chances of being found in various states. Unlike Newtonian physics, where apples, planets and everything else always have well-defined properties, quantum physics is inherently probabilistic. In a sense, particles that are described by wave functions cannot even be said to fully exist; they have no fixed locations, speeds or energies—they have only probabilities.

But everything changes when scientists take a measurement. Then real, tangible properties arise, as if conjured up by merely attempting to observe them. Not only does the theory not say *why* measurements bring about this transformation—it does not tell us why one of those many possibilities manifests instead of others. Quantum mechanics describes what *might* happen as the outcome of a measurement but not what *will* happen. In other words, the theory provides no mechanism for the transition from the probable to the actual.

To "make things happen" in quantum mechanics, one of the theory's legendary founders argued for an almost metaphysical hack. In the late 1920s Werner Heisenberg formulated and spread the notion that the very act of measurement makes the wave function of a particle "collapse"—the many potential outcomes instantaneously reduce to a single observed result. The only flaw with the idea is that there is nothing in the equations of quantum theory that says a collapse occurs or offers a physical process to explain it. Heisenberg's "solution" essentially introduced a new mystery into physics: What exactly happens when a wave function collapses? That quantum conundrum is now known as the measurement problem.

Physicists may have gotten used to the collapse idea over the past 90 years, but they have never really liked it. The notion that a human action—measurement—plays a central role in our most fundamental theory of how the universe works does not sit well with anyone partial to the concept of an objective reality.

"Fundamentally, I have an ideal of what a physical theory should be," says Nobel laureate physicist Steven Weinberg of the University of Texas at Austin. "It should be something that doesn't refer in any specific way to human beings. It should be something from which everything else—including anything you can say systematically about chemistry, or biology, or human affairs—can be derived. It shouldn't have human beings at the beginning in the laws of nature. And yet I don't see any way of formulating quantum mechanics without an interpretive postulate that refers to what happens when people choose to measure one thing or another thing."

CHOOSE YOUR INTERPRETATION

ONE SLEIGHT-OF-HAND WAY OUT of the measurement problem is to assume that collapse simply does not happen. In the early 1970s the late H. Dieter Zeh, then at the University of Heidelberg in Germany, proposed a process that yields the *appearance* of collapse while preserving the full quantum multiplicity of the wave function. In the real world, Zeh argued, the wave function of any particular object becomes hopelessly enmeshed with that of everything else in its environment, making it impossible to keep track of all the countless quantum interactions going on around us. In quantum parlance, the wave functions become "entangled"—a special kind of correlation that preserves connectedness even over huge distances. An observer can only ever hope to look at a single small part of that vast entangled system, so any particular measurement captures just a sliver of the quantum world.

Zeh called this process "decoherence," and it has become the go-to explanation among physicists for why we do not witness quantum phenomena on a macroscopic level. It describes how an intact wave function—which comprises all the possible physical states a particle might have—decoheres as it mingles with the wave functions of other quantum systems around it. If the decoherence model is right, we ourselves live among the strands of that entangled quantum web but see only part of it.

Not all physicists believe that decoherence settles the measurement problem. For one thing, it still fails to explain why we see one strand of the quantum web and not others. "You still have to invoke the collapse postulate, which takes an entangled state and says that one of those possible states has to be selected, and that is usually done by fiat," says Miles P. Blencowe, a theoretical physicist at Dartmouth College. For Blencowe and others, the process does not capture the way we experience things. "I believe we have this one world that is evolving," he says. "How do you go from an entangled state to this perception of the world as always finding one unique path into the future? Many quantum mechanicians would feel that there needs to be a collapse to restore this oneness about the world as it evolves rather than this web of entanglement that keeps enlarging." Adler's assessment of decoherence is more blunt: "It doesn't supply a mechanism [for collapse] at all. It doesn't solve the problem, period."

Six decades ago a doctoral candidate at Princeton University proposed an even more radical solution to the collapse problem. In his 1957 Ph.D. thesis, Hugh Everett argued that the wave function neither collapses nor decoheres. Rather all its components are physically real, parts of an endlessly branching panoply of universes. Everett's "many worlds" interpretation, as it is called, has become popular among cosmologists, who have other reasons to think we might inhabit a multiverse. But no one has ever

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managed to experimentally distinguish the many-worlds idea from standard quantum theory.

The same holds for other interpretations of quantum mechanics. French physicist Louis de Broglie, one of the founders of quantum theory, sought to eliminate the need for collapse by introducing the notion of "pilot waves" that guide the paths of electrons and all other particles. In de Broglie's version of quantum theory, which American physicist David Bohm further developed in the 1950s, there is no mysterious collapse; measurements simply show the interactions of pilot waves and their associated particles. But again, no one has yet found experimental evidence that distinguishes de Broglie and Bohm's pilot-wave view of reality from Everett's many worlds or any of the other dozen or so different takes on quantum mechanics. In the end, quantum partisans choose their favorite description of reality based on aesthetics. "I still come back to the fact that we have this one world that is evolving," Blencowe says. "For that, one really needs some sort of collapse, which is more than just a rule for the results of experiments but is some actual process."

TESTING COLLAPSE

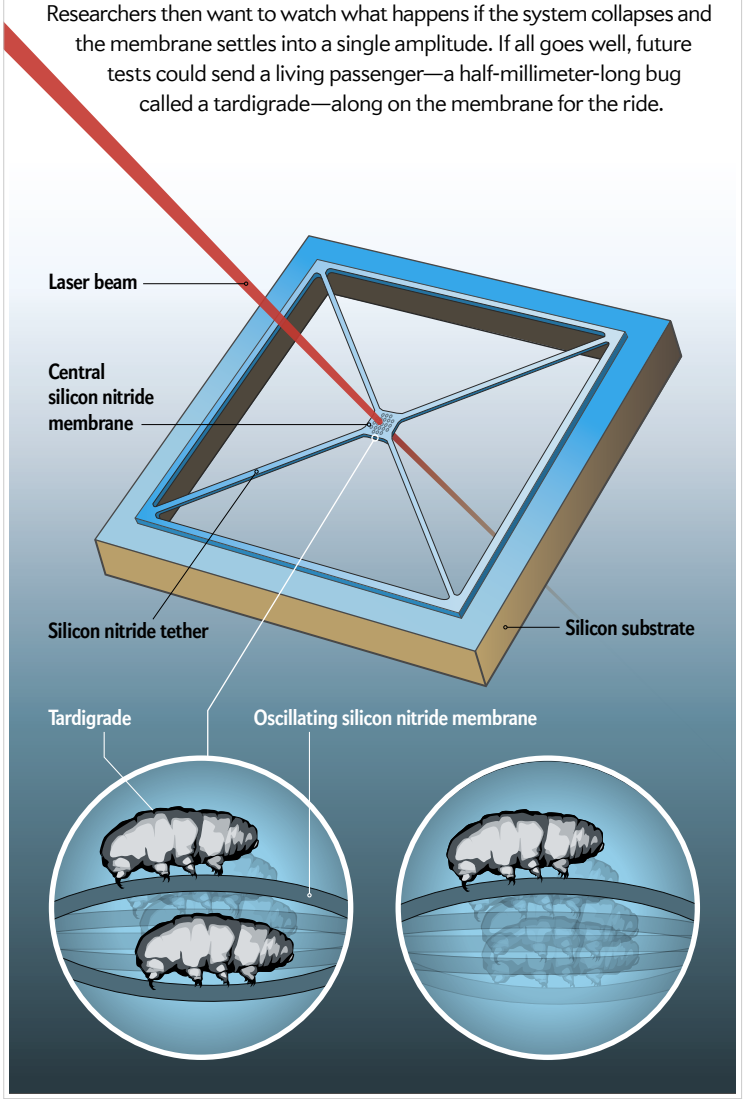
THE CITY OF DELFT might qualify as an entangled quantum system. Its placid canals and medieval brick buildings overlap in space and time with cars, bicyclists, cell-phone shops and students staggering home from all-night parties along the same narrow streets painter Johannes Vermeer once walked. Gröblacher's lab lies about two kilometers south of the old town center and what feels like several hundred years into the future. On a warm spring morning, he shows a visitor one of the "really, really big" things he and his colleagues have built: a millimeter-size membrane tethered to a silicon chip, just barely visible to the naked eye.

Seen up close (or blown up on a poster in the hallway outside Gröblacher's office), the membrane resembles a minuscule trampoline. It is made of silicon nitride, a durable ceramic material that was used for engine bearings in the space shuttles, and holds a highly reflective mirror at its center. A single jolt from a component on the chip can set the membrane vibrating for minutes at a time. Such membranes are "really good oscillators," Gröblacher says. "To put that in perspective, it would be like pushing someone on a swing, and the person would go back and forth, with one single push, for 10 years." Despite its Lilliputian dimensions, the membrane is extraordinarily robust. "We really put a lot of stress in it—six gigapascals" says Richard Norte, one of Gröblacher's collaborators. "It's about 10,000 times the stress you'd have in a bicycle tire, in something that's only about eight times thicker than the width of DNA."

Those robust qualities make the membrane an ideal place to study quantum phenomena—it vibrates reliably at room temperature without breaking down.

Tabletop Test

Physicists want to see if macroscopic objects can behave in quantum ways. One planned experiment will feature a millimeter-size membrane that looks like a tiny trampoline. Attached to a silicon chip, the membrane can be jolted into long-lasting vibrations. Ultimately scientists plan to use a laser to push the membrane into a quantum superposition. In the experiment, the membrane could be vibrating at two different amplitudes at once. Researchers then want to watch what happens if the system collapses and the membrane settles into a single amplitude. If all goes well, future tests could send a living passenger—a half-millimeter-long bug called a tardigrade—along on the membrane for the ride.



Gröblacher and Norte plan to eventually use a laser to nudge the membrane into a superposition—a quantum state where the membrane could be simultaneously oscillating at two different amplitudes. The membrane's ability to wiggle for minutes on end should, in principle, allow such quantum states to persist long enough to see what happens when—or if—the membrane collapses into a single classical state.

"That is exactly what you need to create some sort of quantumness," Gröblacher says. "You don't

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want to have it interact with its environment, because that induces decoherence—supposedly. So you want a really well-isolated system, get it in a quantum state, then switch on your own decoherence, something you control—a laser. We're still not at the point where we can actually create a superposition of the oscillations of the system. But in a few years that's what we're aiming for."

And Gröblacher and his colleagues do not plan to stop there. The researchers hope to ultimately place a living creature on the membrane and then put the membrane, and any passengers on it, into a quantum superposition. Leading candidates for that mission into quantum space are eight-legged microorganisms called tardigrades, also known as water bears. "They're amazing creatures," Gröblacher says. "You can cool them down—they're still alive; you can heat them up—they're still alive; put them in a vacuum—they're still alive." He admits this step is a bit of a ways off. "It's not crazy. It's nice as a long-term goal, but first we have to get our devices into superposition, then we can think about putting in a living organism."

CONTINUOUS SPONTANEOUS LOCALIZATION

WITH OR WITHOUT TARDIGRADES, such an experiment would allow physicists to test whether nature somehow censors quantum effects above a certain size scale. Some physicists have proposed that collapse might be an actual physical phenomenon, with measurable effects. One idea—known as continuous spontaneous localization, or CSL—is that wave function collapse is simply a random event occurring constantly in the microscopic world. According to CSL, the chance that any one particle will collapse is extremely rare—it might happen once in hundreds of millions of years—but for large aggregates of particles, collapse becomes a certainty.

"A single proton has to wait about 10^{16} seconds to see a collapse, so it happens only a few times over the age of the universe," Bassi says. But the huge number of particles in any macroscopic object makes collapse inevitable. "If you take a table, which contains roughly Avogadro's number of particles—10^{24}—the collapse occurs almost immediately." If CSL is real, measurement and observation have no role in collapse. In any measurement, a given particle and the devices recording it become part of an immense quantum array that very rapidly collapses. Although it seems as if the particle went from a superposition to an actual position during a measurement, this transformation happened as soon as the particle interacted with the devices, before the measurement occurred.

If collapse turns out to be a real physical phenomenon, the practical consequences could be significant. For one thing, it might limit the nascent technology of quantum computers. "Ideally, you would like to make bigger and bigger quantum computers," Bassi says. "But you would not be able to run quantum algorithms, because the collapse would kill everything." For decades most physicists have regarded collapse as an essentially untestable aspect of quantum theory. But CSL and other collapse models have changed that. The CSL model, for example, predicts that the action of collapse imparts a slight jiggle to particles, creating an omnipresent background vibration that might be detectable in experiments. "The collapse [in CSL] is something universal for micro and macro systems," Bassi says. "Every time there is a collapse, you move the particle a little." He and other physicists have searched for such evidence in surprising places. They have combed through the calibration data for the Laser Interferometer Gravitational-wave Observatory (LIGO), an instrument capable of registering motions 10,000 times as small as the width of a proton.

MIRRORS at LIGO showed no evidence of having been nudged by quantum jiggles predicted by CSL theory.

LIGO LABORATORY *California Institute of Technology and Massachusetts Institute of Technology*

In February 2016 LIGO reported detecting a gravitational wave for the first time. The wave—a ripple in spacetime caused by two distant colliding black holes—stretched and squeezed the space between two mirrors at the experiment's twin sites in Washington State and Louisiana. This passing wave shifted the positions of LIGO's mirrors by just four-thousandths the diameter of a proton, in perfect agreement with predictions by Einstein's general theory of relativity. But Bassi and his colleagues found no evidence in LIGO's data for any additional motion caused by the kind of quantum nudges predicted by CSL. The result did not surprise them. If quantum collapse is an actual physical phenomenon, it is an extraordinarily weak one. The question was: How

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weak? Now they have put extremely precise bounds on the effect. "If you apply the model to the mirror at LIGO, the mirror should move more than expected, but the mirror doesn't move much. Therefore, the collapse noise can't be too strong," Bassi says.

Physicists have also hunted for signs of collapse in experiments designed to look for dark matter—hypothetical particles thought to account for up to 85 percent of the matter in the universe. One such experiment, sheltered in the Spanish Pyrenees, uses germanium detectors to search for signs of dark matter particles zipping through and generating a flash of x-rays. A collapsing wave function should likewise create a flash, but experimenters have seen no such emissions.

These types of experiments have tightened the constraints on collapse models considerably but not fatally. In September 2017 Andrea Vinante, a physicist at the University of Southampton in England, along with Bassi and three colleagues, reported the discovery of tentative evidence in support of the CSL model. Vinante's team constructed a miniature cantilever (a horizontal beam fixed at one end), just half a millimeter long and two microns thick and tipped with a small magnet. The researchers carefully shielded the setup from any external vibrations and cooled the cantilever to 40 thousandths of a kelvin above absolute zero to eliminate any possibility of thermally induced movements.

Under those conditions the cantilever should have vibrated ever so slightly because of thermal motion of its particles. But the actual wobble was greater than this predictable motion. The experiment's motion detector—an extremely sensitive instrument called a superconducting quantum-interference device, or SQUID—found that the cantilever and its magnet vibrated like a diving board, bending up and down by a few trillionths of a meter. Thirteen years ago Adler calculated that collapsing wave functions might produce vibrations of approximately that size.

"We could see some unexplained noise," says Vinante, describing his experimental results. "It's something that is consistent with what we expect from collapse models, but it could be from an effect we have not understood completely." He and his colleagues are working on upgrades to improve the experiment's sensitivity by at least a factor of 10 and perhaps a factor of 100. "We should be able to either confirm that there is something anomalous or rule out that what we observed was anything interesting." Vinante says it might take another year or two before they have new data. Given the century-long track record of quantum theory's dominance, the odds of discovering a deviation are slim.

But what if one of these experiments does pan out and confirms the phenomenon of quantum collapse? Would that mean an end to the mysteries and paradoxes of the theory? "If collapse really existed, it would divide the world into different scales," says Igor Pikovski, a theoretical physicist at the Center for Astrophysics | Harvard and Smithsonian. "Above a certain scale quantum mechanics would cease to be the correct theory. But below that scale everything we know about quantum mechanics would still hold. So the same philosophical questions and interpretations that bug us would still hold for the lower scale. You'd still have many worlds for electrons or atoms—but not for the moon! So it doesn't solve some of the problems—I think it makes it more strange."

Models such as CSL are just preliminary efforts to unify those two realms. Although they are not full-fledged theories yet, they may eventually help physicists develop a more comprehensive model of reality than quantum mechanics now provides. "My own belief is that you need some modification of quantum mechanics," Adler says. "I don't see why that is a problem. Newtonian mechanics was believed to be exact for 200 years, and it's not. Most theories have a domain in which they work, and then there's a domain beyond which they don't work and where a broader theory is needed."

But for now, at least, quantum mechanics largely seems to withstand every test. "No, we're not facing any crisis. That's the problem!" Weinberg says. "In the past, we made progress when existing theories ran into difficulties. There's nothing like that with quantum mechanics. It's not in conflict with observation at all. It's a problem of failing to satisfy the reactionary philosophical preconceptions of people like me."

Yet for all the weirdness of quantum mechanics, most scientists are happy to leave it be. They carry on using the theory to operate their atom smashers and dark matter detectors and rarely stop to ponder what quantum mechanics says—or does not say—about the fundamental nature of reality. "I think most physicists have what seems to me a very healthy attitude," Weinberg says, "to go on using it, to try to push forward the frontiers of our knowledge and leave the philosophical questions for a future generation." More than a few, though, are not willing to wait that long. "Some people will tell you quantum mechanics has taught us that the world is strange, so we have to accept it," Bassi says. "I would say no. If something is strange, then we have to understand better." SA

Tim Folger is a freelance journalist who writes for *National Geographic, Discover* and other national publications. He is also the series editor for *The Best American Science and Nature Writing,* an annual anthology published by Houghton Mifflin Harcourt.

MORE TO EXPLORE

Mechanical Resonators for Quantum Optomechanics Experiments at Room Temperature. R. A. Norte et al. in *Physical Review Letters,* Vol. 116, No. 14, Article No. 147202; April 8, 2016. Preprint available at https://arxiv.org/abs/1511.06235

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PHOTONS, QUASARS AND THE POSSIBILITY OF FREE WILL

Flickers of light from the edge of the cosmos help physicists advance the idea that the future is not predetermined

By Brian Koberlein

ARTIST'S RENDERING of the distant quasar ULAS J1120+0641.

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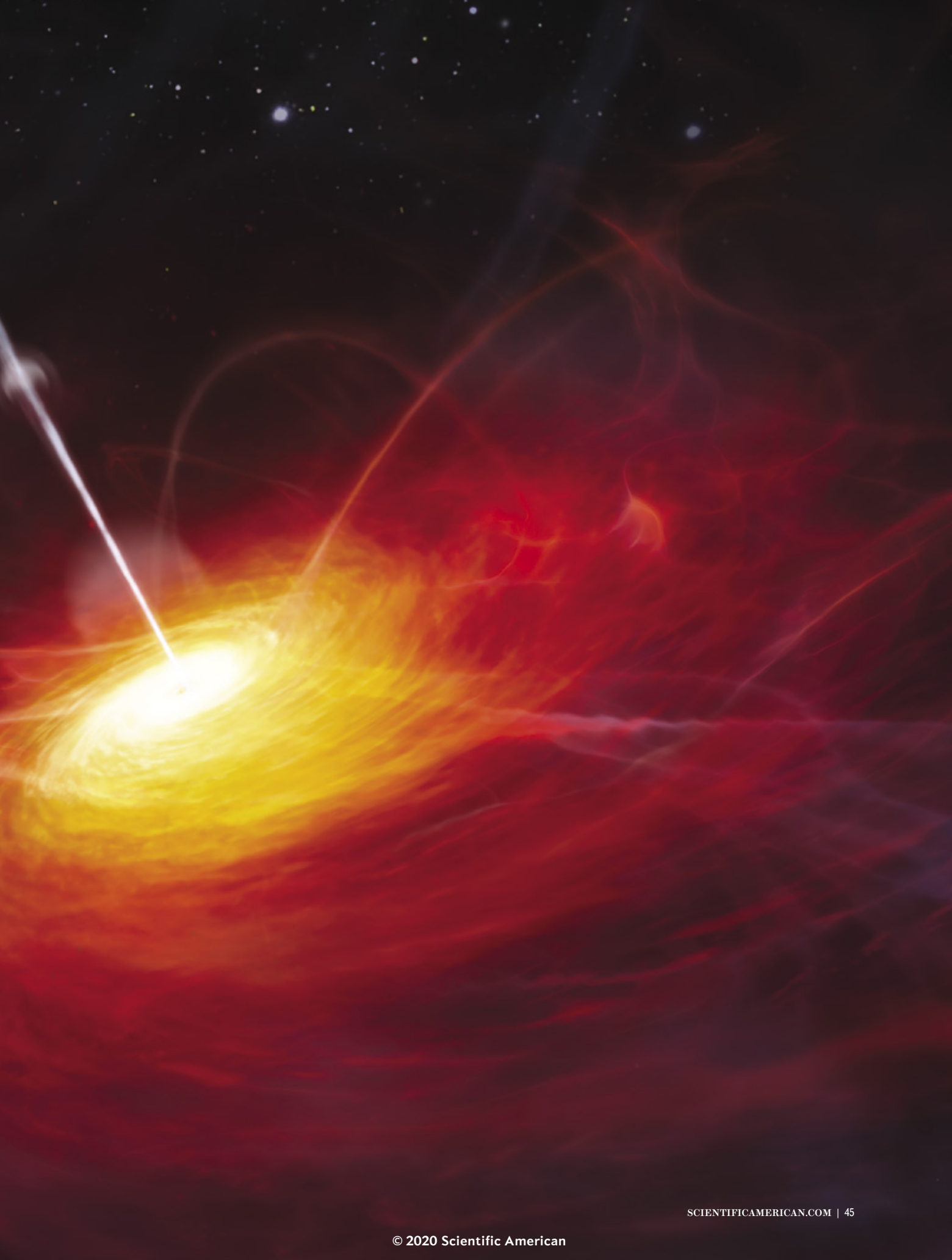

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LIFE IS FULL OF CHOICES.

Do we have a cookie or go to the gym? Do we binge watch our favorite show on Netflix or go to bed at a reasonable time? Our choices have consequences, and we make them of our own free will. Or do we? The nature of free will has long inspired philosophical debates, but it also raises a central question about the fundamental nature of the universe. Is the cosmos governed by strict physical laws that determine its fate from the big bang until the end of time? Or do the laws of nature sometimes allow for things to happen at random? A century-old series of physics experiments still hasn't been able to settle the question, but a new experiment has tilted the odds toward the latter by performing a quantum experiment across billions of light-years.

The laws of classical physics are deterministic. Newton's mathematical cosmos is a clockwork universe, where each cause has a unique effect and we are governed not by our choices but by the rigid laws of nature. Quantum physics, on the other hand, has a property of fuzzy randomness, which some scientists feel could open the door to free will. Because quantum physics lies at the heart of reality, it would seem that randomness wins the day.

Yet some scientists have argued that quantum randomness isn't truly random. If I roll a die, the outcome seems random, but it isn't really. All of its bumps and turns are caused by the forces of gravity and the table in a complex dance, but that dance is deterministic. The moment the die leaves my hand, its fate is sealed, even though I don't know the outcome until it happens. Perhaps quantum objects behave in the same way. Although they seem to act in random ways, they are really governed by some deterministic hidden variables.

It is a question that has fascinated me since graduate school. My dissertation focused on aspects of quantum gravity, a subject that we still don't fully understand. One of the reasons for this is that we don't know how Einstein's deterministic theory of gravity can fit together with the randomness of quantum mechanics.

The question fascinated Einstein as well, and being much smarter than I, he came up with an experiment that could test the idea. Together with Boris Podolsky and Nathan Rosen, both then at the Institute for Advanced Study in Princeton, N.J., he presented a thought experiment now known as the Einstein-Podolsky-Rosen experiment, or EPR experiment for short.

To understand the experiment, suppose we have a mischievous mutual friend named Jane. Whenever Jane wears out a pair of running shoes, she loves to prank us by sending one shoe to each of us. So, whenever you get a shoe in the mail from Jane, you know I've gotten one, too. One of us gets the right shoe, the other the left. But until either of us opens our respective box, neither of us knows which shoe we have. Once the box arrives at your door, you open

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it up and find you have the left shoe. At that moment, you know I must have the right shoe.

This is the basic idea of the EPR experiment. It's nothing more than a silly prank in our everyday world, but for quantum objects it gets really strange. You may have heard of Schrödinger's cat, where a quantum cat is neither alive nor dead until observed in a definite state. Like classical cats, quantum cats like quantum boxes. In the quantum realm, things can be in an indefinite state until you observe them. It would be as if our boxes contained a pair of something (gloves, shoes, salt and pepper shakers, etcetera), but it is impossible to know what specific something until one of us opens their box. Even stranger, how we measure quantum objects determines what the outcome can be. It would be as if opening the box on the side forces it to be a glove, while opening it from the top forces it to be a shoe. How I open my box affects your box miles away. In quantum theory, we say that our two boxes are entangled, so that observing the content of one box also tells us something about the other.

IT LOOKS LIKE THERE ARE NO DETERMINISTIC HIDDEN VARIABLES, AND RANDOMNESS IS STILL POSSIBLE THROUGHOUT THE COSMOS.

We can't do this experiment for gloves and shoes, but we can do it with light. Two entangled photons can be sent in opposite directions. I measure the orientation of one photon at random, you measure the other, and then we compare our results. There are lots of different orientations we would measure, so we can each choose the orientation we want. When this experiment is done in the laboratory, it actually works. And if our measurements are random, there is no way for the photons to know ahead of time which orientation will be measured. So, there can't be any hidden variable to determine the outcome. Whether we get the left or right shoe or the left or right glove, the result is truly random.

This is the heart of why Einstein referred to entanglement as "spooky action at a distance." It's spooky because entangled objects have a quantum connection, even if they are light-years apart. So, a measurement on one object is a measurement on both through this spooky entanglement. But it's only spooky if the measurement we make is random. If it's not random, then no spooky connection is necessary to explain the EPR results.

This is known as the "freedom of choice" loophole. EPR experiments are done in a lab, and even though the choice of how to measure the photons seems random, if there's no free will, then the observation we make was determined by earlier conditions. Because it takes time to set up the experiment in a lab, it's possible that there are small interactions that could let the quantum system know ahead of time what measurement will be done. Maybe the experiment, the scientists and the lab are all entangled in such a way that the outcome isn't truly random, so the quantum objects can game the outcome.

To get around the loophole, you have to deal with the speed of light. It's often said that nothing can travel faster than the speed of light, but it's really information that can't travel faster than light. We can send each other telegrams or text messages, but never faster than the time it takes for light to travel between us. In a small lab, light has plenty of time to travel back and forth across the room while the experiment is being set up, so perhaps small bits of information bias the "random" aspect of experiment before it's even done. That doesn't seem very likely, but a new experiment has overcome this problem. Rather than using a random-number generator in the lab to decide which photon measurement to make, the experimenters used quasars.

Quasars are brilliant beacons of light powered by supermassive black holes in the centers of distant galaxies. The team used random fluctuations in the light from quasars to determine how the photons were measured. Because the light from a quasar has to travel for billions of years to reach us, the fluctuations in brightness happened billions of years before the experiment was done—billions of years before humans even walked the earth. So, there is absolutely no way for it to be entangled with the experiment.

The result was just what quantum theory predicts. Thus, it looks like there really are no deterministic hidden variables, and randomness is still possible throughout the cosmos.

Of course, randomness isn't the only thing necessary for free will. But it does mean that your fate is not necessarily sealed. So, when you resist that second cookie or turn off the TV in the evening, you can take pride in the fact that maybe, just maybe, the choice was yours after all. SA

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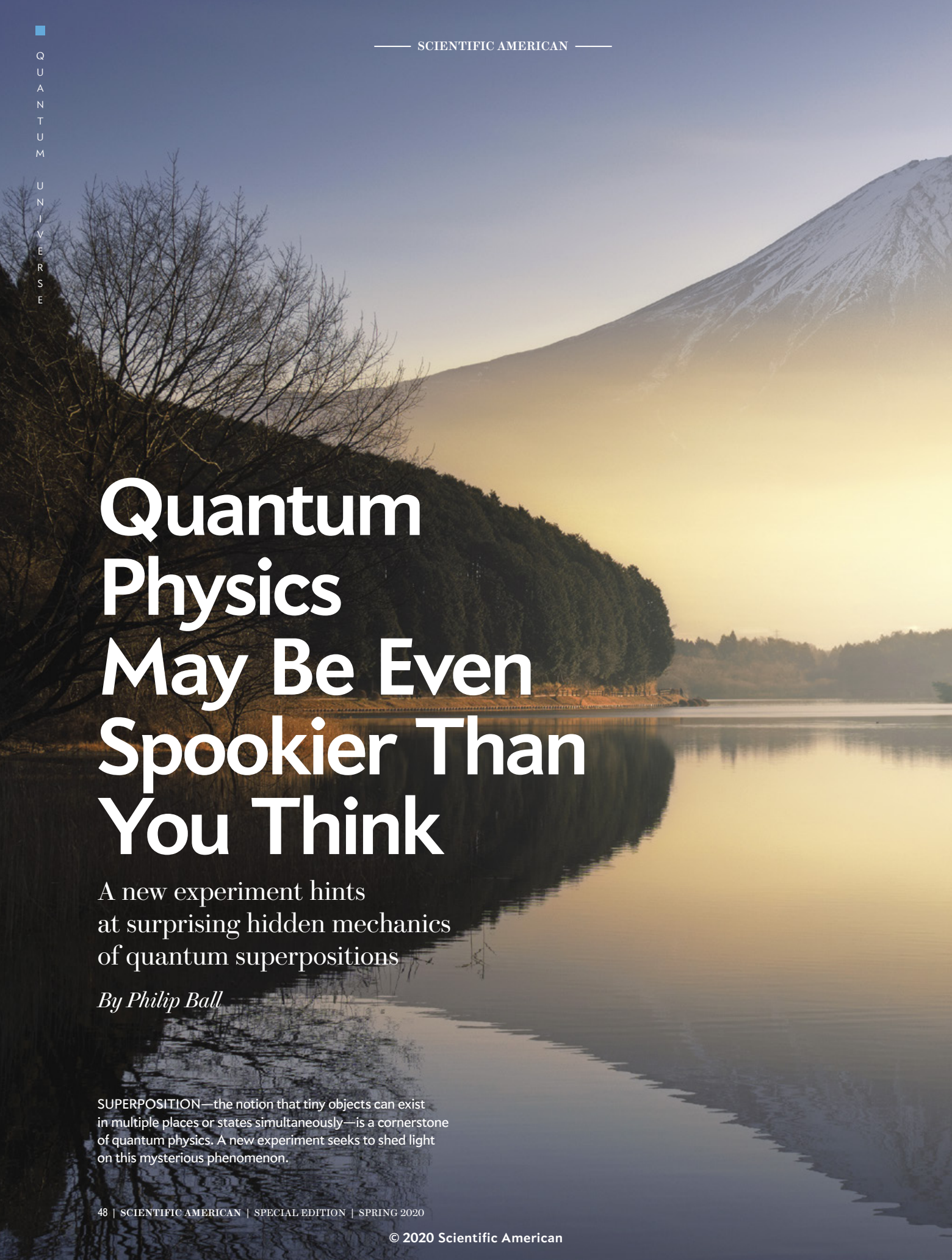

Quantum Physics May Be Even Spookier Than You Think

A new experiment hints at surprising hidden mechanics of quantum superpositions

By Philip Ball

SUPERPOSITION—the notion that tiny objects can exist in multiple places or states simultaneously—is a cornerstone of quantum physics. A new experiment seeks to shed light on this mysterious phenomenon.

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IT IS THE CENTRAL QUESTION IN QUANTUM MECHANICS, AND NO ONE knows the answer: What really happens in a superposition—the peculiar circumstance in which particles seem to be in two or more places or states at once? In 2018 a team of researchers in Israel and Japan proposed an experiment that could finally let us say something for sure about the nature of this puzzling phenomenon.

Their experiment was designed to enable scientists to sneak a glance at where an object—in this case a particle of light, called a photon—actually resides when it is placed in a superposition. And the researchers predict the answer will be even stranger and more shocking than "two places at once."

The classic example of a superposition involves firing photons at two parallel slits in a barrier. One fundamental aspect of quantum mechanics is that tiny particles can behave like waves, so that those passing through one slit "interfere" with those going through the other, their wavy ripples either boosting or canceling one another to create a characteristic pattern on a detector screen. The odd thing, though, is this interference occurs even if only one particle is fired at a time. The particle seems somehow to pass through both slits at once, interfering with itself. That's a superposition.

And it gets weirder: Measuring which slit such a particle goes through will invariably indicate it only goes through one—but then the wavelike interference (the "quantumness," if you will) vanishes. The very act of measurement seems to "collapse" the superposition. "We know something fishy is going on in a superposition," says physicist Avshalom Elitzur of the Israeli Institute for Advanced Research. "But you're not allowed to measure it. This is what makes quantum mechanics so diabolical."

For decades researchers have stalled at this apparent impasse. They cannot say exactly what a superposition is without looking at it, but if they try to look at it, it disappears. One potential solution—developed by Elitzur's former mentor, Israeli physicist Yakir Aharonov, now at Chapman University, and his collaborators—suggests a way to deduce something about quantum particles before measuring them. Aharonov's approach is called the two-state-vector formalism (TSVF) of quantum mechanics and postulates quantum events are in some sense determined by quantum states not just in the past—but also in the future. That is, the TSVF assumes quantum mechanics works the same way both forward and backward in time. From this perspective, causes can seem to propagate backward in time, occurring after their effects: a phenomenon called retrocausation.

But one needn't take this strange notion literally. Rather in the TSVF, one can gain retrospective knowledge of what happened in a quantum system by selecting the outcome: Instead of simply measuring where a particle ends up, a researcher chooses a particular location in which to look for it. This is called post-selection, and it supplies more information than any unconditional peek at outcomes ever could. This is because the particle's state at any instant is being evaluated retrospectively in light of its entire history, up to and including measurement. The oddness comes in because it looks as if the researcher—simply by choosing to look for a particular outcome—then causes that outcome to happen. But this is a bit like concluding that if you turn on your television when your favorite program is scheduled, your action causes that program to be broadcast at that very moment. "It's generally accepted that the TSVF is mathematically equivalent to standard quantum mechanics," says David Wallace, a philosopher of science at the University of Southern California, who specializes in interpretations of quantum mechanics. "But it does lead to seeing certain things one wouldn't otherwise have seen."

Take, for instance, a version of the double-slit experiment devised by Aharonov and his co-worker Lev Vaidman of Tel Aviv University in 2003, which they interpreted with the TSVF. The pair described (but did not build) an optical system in which a single photon acts as a "shutter" that closes a slit by causing another "probe" photon approaching the slit to be reflected back the way it came. By applying postselection to the measurements of the probe photon, Aharonov and Vaidman showed, one could discern a shutter photon in a superposition closing both (or indeed arbitrarily many) slits simultaneously. In other words, this thought experiment would in theory allow one to say with confidence the shutter photon is both "here" and "there" at once. Although this situation seems paradoxical from our everyday experience, it is one well-studied aspect of the so-called nonlocal properties of quantum particles, where the whole notion of a well-defined location in space dissolves.

In 2016 physicists Ryo Okamoto and Shigeki Takeuchi of Kyoto University verified Aharonov and Vaidman's predictions experimentally using a light-carrying circuit in which the shutter photon is created using a quantum router, a device that lets one photon control the route taken by another. "This was a pioneering experiment that allowed one to infer the simultaneous position of a particle in two places," says Elitzur's colleague Eliahu Cohen of the University of Ottawa in Ontario.

Now Elitzur and Cohen have teamed up with Okamoto and Takeuchi to concoct an even more mind-boggling experiment. They believe it will enable researchers to say with certainty something about the location of a particle in a superposition at a series of different points in time—before any actual measurement has been made.

This time the probe photon's route would be split into three by partial mirrors. Along each of those paths it may interact with a shutter photon in a superposition. These interactions can be considered to take place within boxes labeled A, B and C, one of which is situated along each of the photon's three possible routes. By looking at the self-interference of the probe photon, one can retrospectively conclude with certainty the shutter particle was in a given box at a specific time.

The experiment is designed so the probe photon can only show

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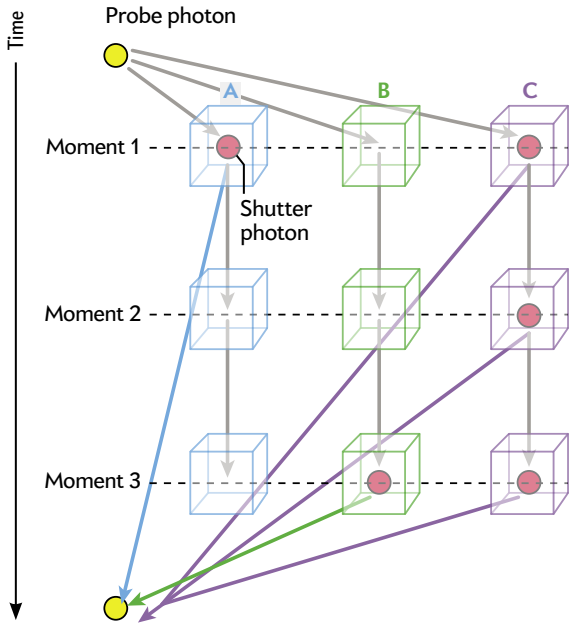
The Jumpy Shutter



A probe photon (*yellow, left*) is sent in a superposition through the three boxes A, B and C simultaneously to see if the shutter photon (*red*) is inside them. If it is, the probe photon is reflected: This lets the probe "report" on where the shutter photon is without looking at it directly. The shutter photon is placed in a superposition that makes its location within the boxes vary through time: At t_1 (moment 1), it is in A and C but not B; at t_2, it is only in C (and definitely not in A or B); and at t_3, it is in B and C but not A. The result: Although it is in C in all times, the shutter photon seems to be first in A but not B, then to vanish from A, then to reappear in B. So this superposition is not "in all places at once" but rather in some places some of the time.

interference if it interacted with the shutter photon in a particular sequence of places and times: namely, if the shutter photon was in both boxes A and C at some time (t_1), then at a later time (t_2) only in C, and at a still later time (t_3) in both B and C. So interference in the probe photon would be a definitive sign the shutter photon made this bizarre, logic-defying sequence of disjointed appearances among the boxes at different times—an idea Elitzur, Cohen and Aharonov proposed as a possibility in 2017 for a single particle spread across three boxes. "I like the way this paper frames questions about what is happening in terms of entire histories rather than instantaneous states," says physicist Ken Wharton of San José State University, who is not involved in the new project. "Talking about 'states' is an old pervasive bias, whereas full histories are generally far more rich and interesting."

That richness, Elitzur and his colleagues argue, is what the TSVF gives access to. The apparent vanishing of particles in one place at one time—and their reappearance in other times and places—suggests an extraordinary vision of the underlying processes involved in the nonlocal existence of quantum particles. Through the lens of the TSVF, Elitzur says, this flickering, ever changing existence can be understood as a series of events in which a particle's presence in one place is "canceled" by its own "counterparticle" in the same location. He compares this with the idea introduced by British physicist Paul Dirac in the 1920s, who argued that particles possess antiparticles, and if brought together, a particle and antiparticle can annihilate each other. At first this notion seemed just a manner of speaking but soon led to the discovery of antimatter. The disappearance of quantum particles is not "annihilation" in this same sense, but it is somewhat analogous: these putative counterparticles, Elitzur posits, should possess negative energy and negative mass, allowing them to cancel their counterparts.

So although the traditional "two places at once" view of superposition might seem odd enough, "it's possible a superposition is a collection of states that are even crazier," Elitzur says. "Quantum mechanics just tells you about their average." Postselection then allows one to isolate and inspect just some of those states at greater resolution, he suggests. Such an interpretation of quantum behavior would be, he says, "revolutionary"—because it would entail a hitherto unguessed menagerie of real (but very odd) states underlying counterintuitive quantum phenomena.

Okamoto and his colleagues in Kyoto have now carried out the proposed experiment using photons, but they are still analyzing the results. All the same, Cohen says, "the preliminary results accord well with the theory." He says the Japanese researchers are now making improvements to the setup to shrink the error bars.

For now some outside observers are not exactly waiting with bated breath. "The experiment is bound to work," Wharton says—but he adds it "won't convince anyone of anything, since the results are predicted by standard quantum mechanics." In other words, there would be no compelling reason to interpret the outcome in terms of the TSVF rather than one of the many other ways that researchers interpret quantum behavior.

Elitzur agrees their experiment could have been conceived using the conventional view of quantum mechanics that prevailed decades ago—but it never was. "Isn't that a good indication of the soundness of the TSVF?" he asks. And if someone thinks they can formulate a different picture of "what is really going on" in this experiment using standard quantum mechanics, he adds, "Well, let them go ahead!"

He is confident that the work heralds "nothing short of a revolution within quantum mechanics." Now that measurement methods have become precise enough, he says, "you can be sure that notions like retrocausation are going to become part and parcel of quantum reality."

Philip Ball is an editor at *Nature*. He also writes a regular column for *Chemistry World*.

MORE TO EXPLORE

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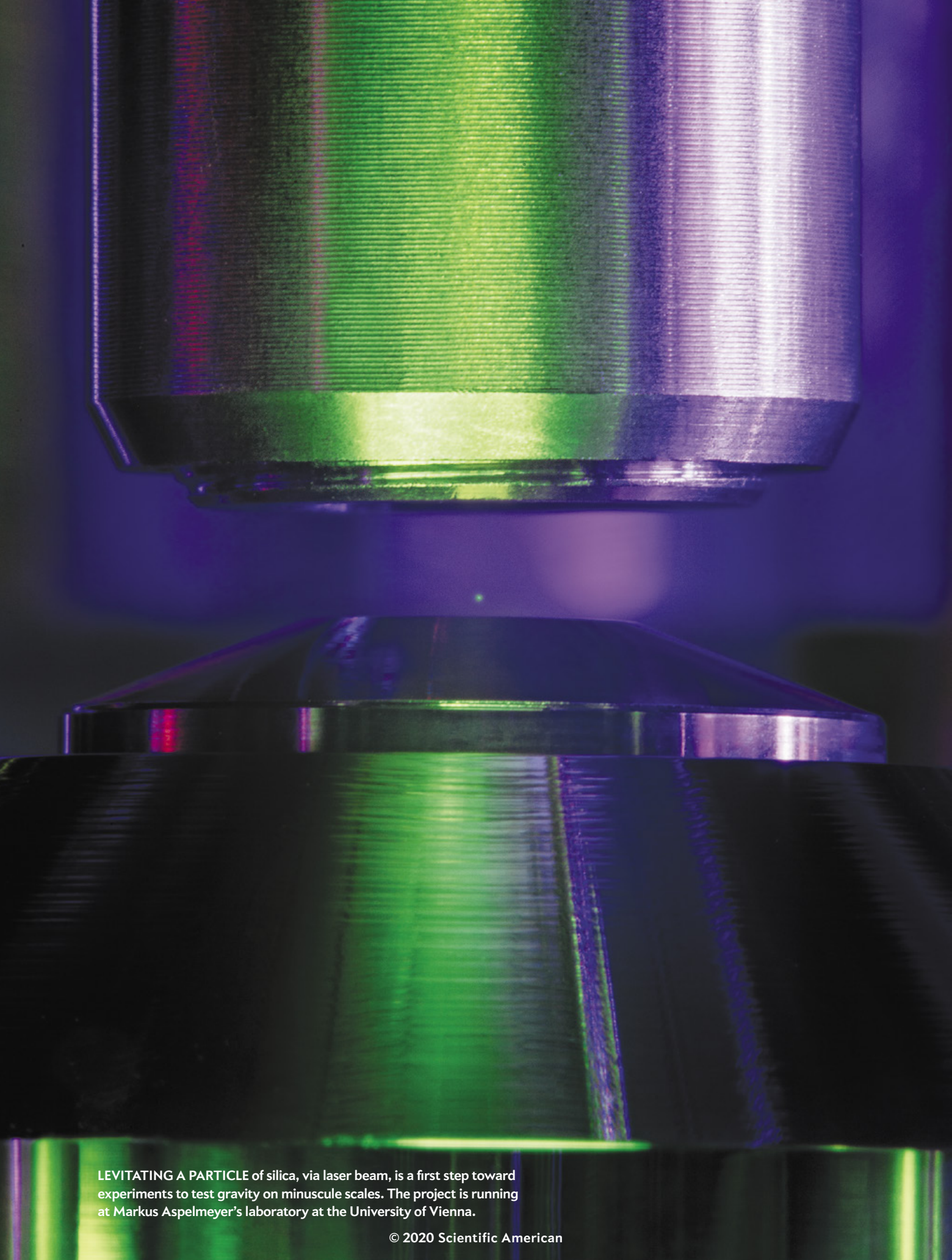

LEVITATING A PARTICLE of silica, via laser beam, is a first step toward experiments to test gravity on minuscule scales. The project is running at Markus Aspelmeyer's laboratory at the University of Vienna.

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QUANTUM GRAVITY IN THE LAB

Physicists attempting to unify the theories of gravity and quantum mechanics have long thought practical experiments were out of reach, but new proposals offer a chance to test the quantum nature of gravity on a tabletop

By Tim Folger

IN BRIEF

To unify the famously uncooperative theories of quantum mechanics and general relativity, scientists will likely have to reach down to the unimaginably small realm of the "Planck scale." Practical experiments probing this scale have long been thought impossible, but several new proposals stand to change that.

Physicists are hoping that by making extremely precise measurements of gravity in small-scale setups—experiments that will fit onto a tabletop in a laboratory—they can detect effects from the intersection of gravity and quantum theory.

The experiments aim to show whether gravity becomes quantized—that is, divisible into discrete bits—on extremely tiny scales.

Photographs by Mattia Balsamini

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IN 1797 HENRY CAVENDISH, ONE OF GREAT BRITAIN'S leading scientists, built a contraption to weigh the world.

At the time, Earth's mass was unknown, as was its composition. Was it mostly solid rock? Did it vary with depth? Astronomer Edmond Halley even suggested that Earth might be hollow. Isaac Newton had compared Earth's mass with that of other bodies in the solar system and knew, for example, that Earth was more massive than the moon. He had even suggested a way to determine Earth's *absolute* mass: measure the gravitational attraction between two small spherical masses with great accuracy, then extrapolate Earth's own mass from the result. But Newton summarily dismissed his own idea—he thought the attraction between the spheres would be too small to detect, even with impractically large masses. "Nay, whole mountains will not be sufficient to produce any sensible effect," he wrote in his masterpiece, the *Principia,* which laid out his laws of motion and gravitation.

On an August day more than a century later Cavendish proved Newton wrong. The device he had built in a shed on his estate in southwest London consisted of two 1.6-pound lead balls attached to opposite ends of a six-foot-long wood rod, which hung from a wire fastened to an overhead beam. Two much heavier lead spheres, each weighing nearly 350 pounds, were suspended separately about nine inches away from the lighter balls. Cavendish expected that the gravitational pull of the heavy spheres on the smaller ones would make the wood rod rotate ever so slightly, and he was right—it moved just over a tenth of an inch.

This allowed him to directly measure the gravitational force exerted by each of the larger spheres on the smaller ones. Because he already knew that Earth exerted a gravitational force of 1.6 pounds on each of the small spheres (in the English system of units, a pound is by definition a measure of force), Cavendish could set up a simple ratio: the gravitational force between the small sphere and the large sphere compared with the gravitational force between the small sphere and Earth. Because the gravitational force is directly proportional to the masses being measured, he could use that ratio to solve for Earth's unknown mass. Over the course of nine months he repeated the experiment 17 times and found that Earth weighed 13 million billion billion pounds, a result essentially identical to the best modern estimates.

"It's an incredible story," says Markus Aspelmeyer, who has been recounting the Cavendish experiment during a Skype call. "It was the first precision tabletop experiment [with gravity]." Cavendish's 220-year-old tour de force, though not actually conducted on a tabletop, is a source of inspiration for Aspelmeyer, a physicist at the University of Vienna in Austria. Like Cavendish, he has plans for an ambitious, seemingly impossible experiment, one that might transform our understanding of gravity: he wants to use a small-scale setup—literally on a tabletop in his lab—to find evidence that gravity might be a quantum phenomenon.

Of the four fundamental forces in the universe, gravity is the only one that cannot be described by the laws of quantum mechanics, the theory that applies to all other forces and particles known to physics. Electromagnetism; the "strong" nuclear force that binds atomic nuclei; and the "weak" nuclear force that causes radioactive decay—they are all quantum to the core, leaving gravity as a sole, mysterious outlier.

This exception has vexed physicists since Albert Einstein's heyday. Einstein never managed to unify his own theory of gravity—the general theory of relativity—with quantum mechanics. Most physicists who now work on the problem believe that the unification occurs when we zoom in on the cosmos to what is called the Planck scale, after Max Planck, one of the founders of quantum theory. Distances on the Planck scale are so tiny—100 trillion trillion times as small as a hydrogen atom—that spacetime itself is thought to assume quantum characteristics. A quantum spacetime would no longer be the smooth continuum described by general relativity; it would be coarse-grained, like a digital photograph that becomes pixelated when magnified. That graininess is a hallmark of quantum theory, which confines the energy, momentum and other properties of particles to discrete bits, or quanta. But what exactly is a quantum of spacetime? How could time or distance be measured if space and time themselves are fractured like broken rulers?

"All our theories of physics either explicitly or implicitly require the existence of rods and clocks: something occurred [here] at this time and then did

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2

this [there] at a later time," says Miles Blencowe, a theoretical physicist at Dartmouth College. "Where do you start if you don't even have a time parameter or a distance parameter?" Lajos Diósi, a theoretical physicist at the Wigner Research Center for Physics in Budapest, sums up the conundrum this way: "We don't know what will be there, but we know for sure that there will be a total scrambling of the spacetime continuity if you go down to the Planck scale."

Unfortunately for physicists, there is no way to observe phenomena on the Planck scale and thus no way to check the predictions of various theories of quantum gravity to see which of them might be right. "The situation is not that we do not have theories of quantum gravity," says Carlo Rovelli, a theoretical physicist at Aix-Marseille University in France. "We do. The problem is that we have more than one."

In physics, the higher the energy scale of your experiment, the smaller the distance you can probe. And probing the Planck scale directly would require a machine more than 15 orders of magnitude more powerful than CERN's Large Hadron Collider (LHC) near Geneva, the largest particle accelerator ever built, with a circumference of 27 kilometers. As one physicist says, such an accelerator would need to be roughly the size of our galaxy. Machines such as the LHC bash particles together at nearly the speed of light, and physicists hope something new will emerge from the debris. The basic approach is not much different from blowing up a safe to find out what is inside. The practitioners of tabletop physics aim to replace brute force with finesse, like safecrackers listening to the tumblers of a lock clicking into place. "You're trading high energy for high precision is the way I look at it," says Eric Adelberger, a physicist at the University of Washington. "There's the energy frontier, and there's the precision frontier. If you can measure something really, *really* well, you can test physics that's going on at some really high-energy scale." Now at least three groups, including Aspelmeyer's, are designing experiments to do just that. The scientists are optimistic that these projects will finally reach the levels of precision needed to probe into the realm where gravity goes quantum.

A THOUGHT EXPERIMENT

TO UNDERSTAND WHY PRECISION allows physicists to indirectly access higher energies, and thus smaller scales, consider a historical analogue: Brownian motion. In a paper published in 1905, Einstein showed that the puzzling random movements of pollen grains in a jar of water could be explained by collisions with water molecules, even though the molecules themselves were many orders of magnitude too small to be observed directly. Aspelmeyer and other physicists are betting that the unobservably small things happening in the Planckian realm might similarly influence phe-

SUPERCONDUCTING CIRCUITS (*1*) aid the levitation experiment. Researchers are also trying to measure the gravitational fields of millimeter-wide gold spheres (*2*) to observe gravity closer to the quantum realm.

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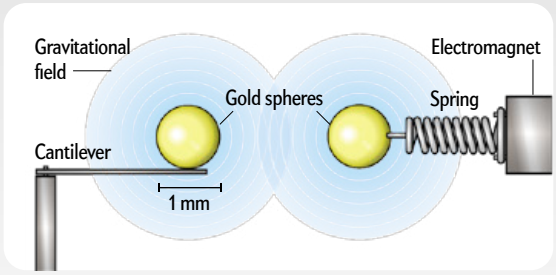
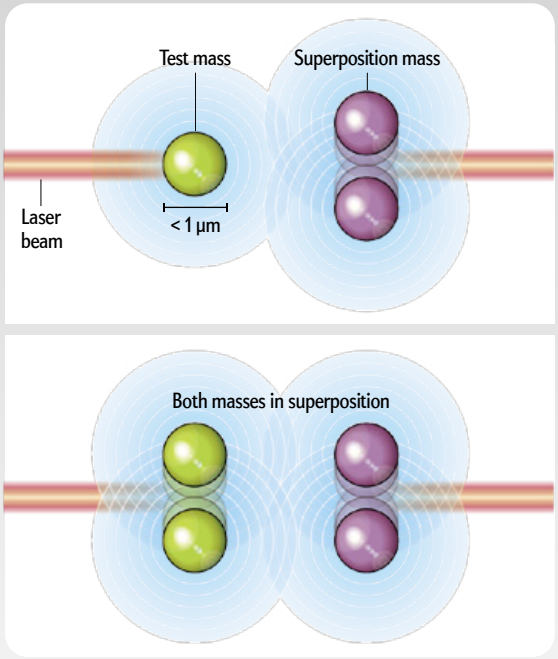
Quantum Gravity Experiments

To understand whether gravity fits into quantum theory, physicists are designing experiments to measure gravitational fields with extreme precision to search for signs of quantum behavior. Such behavior might include "superposition"—the ability of quantum particles to occupy two places simultaneously—and "entanglement"—a kind of connection between quantum objects where their fates become intertwined. If researchers can find evidence of gravitational fields displaying superposition or entanglement, they will know that gravity has quantum properties.



PRELIMINARY EXPERIMENT #1
One experiment, proposed by physicist Markus Aspelmeyer, will ultimately attempt to put a mass into a superposition state of being in two locations simultaneously and then try to see if the gravitational field of the mass splits into two as well. A preliminary version of this trial will develop the technology to detect gravitational fields of smaller objects than ever before—in this case, two tiny gold spheres. An electromagnet attached to a spring will cause one ball to vibrate, and the other, at the end of a cantilever, should oscillate in response to the changing gravitational pull.



ULTIMATE EXPERIMENT #1
Eventually the team will aim to put one of these spheres into a state of superposition. If this ball's gravitational field goes into superposition, too, and exists in two places, then the other mass should feel the pull of both fields and become entangled, entering superposition as well.

nomena accessible to tabletop experiments. And although particle accelerators cannot be upgraded by orders of magnitude—we are unlikely to see accelerators with 1,000-kilometer circumferences—the precision of tabletop experiments may well improve by a few orders of magnitude in the decades ahead.

Such gains might allow Aspelmeyer to test a key assumption shared by all theories of quantum gravity: that gravity itself should display some profoundly strange quantum properties. "If that is really true, there should be some consequences for phenomena at an energy scale that is much much smaller [than the high energies that correspond with the Planck scale]"—that is, at roughly the scale we inhabit, Aspelmeyer says. "The question is: Can we come up with experiments that possibly test those consequences?"

What Aspelmeyer has in mind is an experiment that would measure the gravitational attraction between two spherical masses. Unlike Cavendish, though, Aspelmeyer will not be weighing Earth, and his milligram masses are orders of magnitude smaller than Cavendish's lead balls. He wants to test whether gravity interacts at all with the quantum properties of small masses. Specifically, he intends to look at what kind of gravitational effects might be generated by an object placed in a "Schrödinger's cat"-like state of being both here and there at once.

In the quantum world, particles have the uncanny ability to be in two places simultaneously—a superposition, as physicists call it. Scientists have observed quantum superpositions many times in laboratories, but they are delicate states. Interactions with any nearby particles quickly cause objects in superposition to "collapse" into a single position. But while the superpositions last, Aspelmeyer wonders what properties these particles have. Do they create their own minuscule gravitational fields, for instance? "Imagine you place an object in a superposition," he says, "and now you ask a question: How does it gravitate? That is the question we want to answer."

The experiment Aspelmeyer hopes to carry out was first proposed as a *gedankenexperiment*—a thought

Illustration by Ben Gilliland

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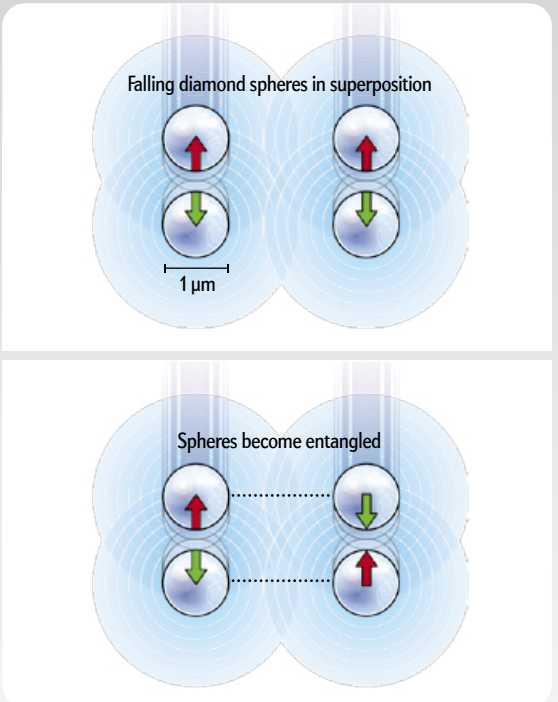

EXPERIMENT #2

A second experimental concept, proposed by two groups (by Sougato Bose and his colleagues and, independently, by Chiara Marletto and Vlatko Vedral), would drop two diamond spheres side by side for a couple of seconds. If the spheres are just 100 microns apart, the proximity of their gravitational fields should cause the spheres to become entangled, the physicists reason. If that happens, the experimenters will detect a correlation between the direction of their spins after the drop. If the particles do not become entangled—presumably because gravity does not experience this quantum phenomenon—then the spins should be random.

experiment—by the legendary physicist Richard Feynman at a conference in 1957. Feynman argued that if gravity is indeed a quantum phenomenon, a superposition of a particle in two places at once would create two separate gravitational fields. According to the general theory of relativity, gravitational fields are distortions of space and time. Thus, in the case of a small mass in a quantum superposition, two different spacetimes would coexist side by side, almost like two separate mini universes, a state of affairs that should not exist in Einstein's theory.

If that spacetime superposition arose, how would another object—a test mass—interact with it? Would the motion of the test mass indicate that it had felt the pull of two different gravitational fields? Or would the interaction cause the superposition to collapse, as some physicists believe, resulting in normal gravitational dynamics? If the superposition persisted and if the test mass *did* interact with the superposition's gravitational fields, it would be strong evidence that the test mass and the superposition had become "entangled"—a telltale feature of quantum mechanics where the properties of two separate particles become inextricably linked. Feynman argued that because only quantum phenomena can become entangled, the experiment would show that gravity, like all other known forces in the universe, is fundamentally quantum.

Such an outcome would not in itself validate any particular theory of quantum gravity, but it would be indirect evidence that gravity is quantized on the Planck scale. Even more broadly, the experiment would provide compelling evidence that the laws of quantum mechanics hold at *all* scales, not just in the realm of photons, atoms and other fundamental particles. Some physicists have clung to the idea that quantum mechanics might break down when it comes to describing the macroscopic world. Roger Penrose, for example, a physicist at the University of Oxford, and Diósi have suggested that gravity causes superpositions above a certain size to collapse, effectively dividing the quantum world from the so-called classical one.

"One of the areas where quantum theory is supposed to fail is when it comes to describing gravity," says Chiara Marletto, a theoretical physicist at Oxford. "There have been a number of eminent scientists who maintain that gravity will be exactly the place where quantum theory breaks down. So, instead of having a quantized [theory of] gravity, we should actually make quantum theory classical for it to describe gravity." In this way of thinking, quantum theory might need to be modified to make it consistent with general relativity, rather than trying to fit gravity into quantum theory as it is.

TURNING THOUGHT INTO REALITY

THE TECHNOLOGY AND EXPERTISE needed to decide the issue did not exist when Feynman came up with his idea, and even now the project remains daunting. For several years now Aspelmeyer's lab has been pushing to measure the gravitational fields of ever smaller masses. It is a tricky undertaking: Earth's enormous gravity swamps the fields of even relatively large objects. The smallest mass for which a gravitational field has been measured so far is a 700-milligram tungsten sphere. That is about the mass of a paper clip or a raisin—a gargantuan object compared to quantum particles.

To realize Feynman's thought experiment, Aspelmeyer and his colleagues will need to work with ob-

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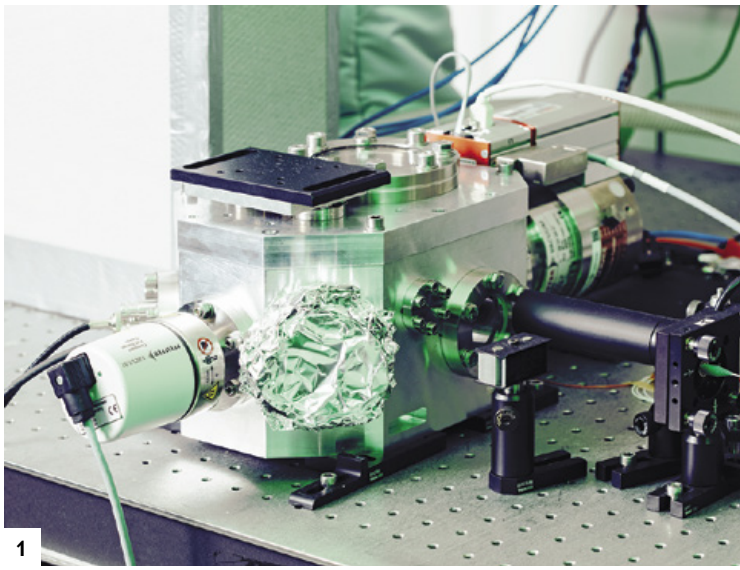
jects considerably smaller than paper clips. They are now developing a prototype experiment to detect the gravitational fields of millimeter-wide gold spheres (gold was chosen for its density and purity) weighing just a few tens of milligrams. "That's a factor of tens or hundreds less heavy than anything else that has been measured so far," Aspelmeyer says. In the experiment, the researchers will place two gold spheres a few millimeters apart, with one attached to a small, spring-mounted magnet and the other fixed to the end of a micromechanical cantilever. When the electromagnet is turned on, the sphere on the spring will start vibrating, creating a changing gravitational field that in turn makes the mass on the cantilever bounce up and down like a diver on a board. The cantilever's motion—tracked by lasers—essentially amplifies the gravitational force of the sphere attached to the spring, making it easier to detect against the background of Earth's field.



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After honing their gravitational-measuring skills with ordinary, nonquantum masses, Aspelmeyer's team would then tackle superpositions. If he could put two small spheres into superpositions, Aspelmeyer could test how their gravitational fields interacted. The results could suggest that the particles were entangled, supporting Feynman's intuition about gravity's quantum nature.

A quantum spacetime would no longer be the smooth continuum described by general relativity; it would be coarse-grained.

What will it take to pull all this off? To have a realistic shot at creating a quantum superposition, Aspelmeyer will need to shrink his millimeter-size gravitational test masses down to fractions of a micron—a 1,000-fold reduction. At the same time, he will need superpositions of objects that are massive enough to have detectable gravitational fields. For that he will likely draw on the talents of a colleague at Vienna, Markus Arndt, who holds the record for the largest object ever placed in a superposition: a behemoth of a molecule containing more than 800 atoms. And instead of being stuck to springs and cantilevers, the masses would be suspended in space with "optical tweezers"—tightly focused laser beams.

"If I can detect the gravitational field of an object over which I can obtain quantum control, then I am in business," Aspelmeyer says. "This would be the long-term dream—not tomorrow, not in five years. Both from the top down and bottom up—from making [the gravitational] masses smaller and making the [superposition] masses larger—we think we know how to get there and bring those two domains together. Now we just need to work hard."

Arndt, Aspelmeyer's likely collaborator, says the experiment presents a host of challenges: the small, spherical masses will be difficult to isolate gravitationally and prone to interacting with any nearby surface. "There are so many effects that are hard to suppress," he says. "Still, it has to be tried, by all means. If we don't start now, it won't be done in 10 years." Arndt compares the effort that will be required with the search for gravitational waves, a phenomenon predicted by Einstein's general theory of relativity. In 2015 the giant Laser Interferometer Gravitational-wave Observatory (LIGO) finally detected the first gravitational wave, but the discovery was a long time coming. "It was a 40-year effort to get the gravitational-wave detector going," Arndt says.

THE LAST REFUGE OF QUANTUM HOLDOUTS

ASPELMEYER IS NOT THE ONLY PHYSICIST working on the problem. In December 2017 two independent groups simultaneously published their own very similar takes on Feynman's thought experiment. Sougato Bose, a physicist at University College London, and his colleagues and Marletto and her Oxford colleague Vlatko Vedral described a way to test for the gravitational entanglement between superpositions of microscopic particles without having to measure their gravitational fields.

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VACUUM CHAMBERS (*1, 2*) **isolate small masses from the outside world to measure their gravitational fields with minute precision.**

In the proposed experiment, pairs of micron-wide diamond spheres would be put into superpositions and allowed to fall in a vacuum for a couple of seconds in Earth's gravitational field. If the spheres were close enough together—about 100 microns apart, according to Bose's estimates—their gravitational fields should cause the particles to become entangled. When that happens, the properties of the entangled particles will instantaneously correlate in ways that are not possible in classical physics. One particle's spin, for example—whether it points up or down in a magnetic field—will flip in the opposite direction as soon as the spin of its entangled partner is measured.

By tracking how often such correlations occur—Bose says that 10,000 trials should yield an answer—he, Marletto and Vedral could determine whether the falling diamonds had indeed become entangled. Once again, entanglement would suggest that gravity itself must have quantum properties. "Our work will prove that gravity is quantum in the sense that it obeys the superposition principle," Bose says. The experiment faces many of the same challenges that Aspelmeyer's does: the need for large superpositions that last for seconds at a time and stay close enough together so that gravity can entangle them. "That makes the thing very difficult," Bose says. "But I'm sure I'll see it in my lifetime."

Both experiments, if they pan out, would give physicists their first indirect evidence that gravity—and therefore spacetime itself—must be quantized on the Planck scale. And that is an exciting prospect for Rovelli and other quantum gravity theorists, who have spent years working on theories without any experimental feedback. "I think it's a game changer, this idea, the attempt to see quantum gravity in the lab," Rovelli says. "As far as we know [gravity's quantum nature] should definitely be real; otherwise we haven't learned a thing about the world."

A century after its birth quantum mechanics remains the most baffling of scientific theories. Some physicists, most famously Einstein, doubted that it could be the final word on the nature of reality. Yet countless experiments have confirmed the theory's predictions, typically with multidecimal-point accuracy. In some sense, the question of whether gravity is quantum or classical represents a last refuge for those who feel that there must be *something* wrong with quantum mechanics. If these tabletop experiments succeed, that refuge will crumble.

"Quantum theory teaches us a completely different way of describing what we can say about nature," Aspelmeyer says. "The rule book that we have found through quantum theory is a fundamental one and has to apply in general to all the theories we have." SA

Tim Folger is a freelance journalist who writes for *National Geographic, Discover* and other national publications. He is also the series editor for *The Best American Science and Nature Writing,* an annual anthology published by Houghton Mifflin Harcourt.

MORE TO EXPLORE

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QUANTUM CHESHIRE CATS

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A proposed experiment to swap fundamental properties between photons carries profound implications for our understanding of reality itself

By Anil Ananthaswamy

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ONE OF THE MOST MIND-BENDING REVELATIONS OF QUANTUM physics over the past century has been that properties of particles are possibly not real until they are measured. Now a new thought experiment suggests that conclusion may be too tame: it seems that particles' properties—their spin, for instance—may not even belong to them. This possibility is akin to saying that your personality does not belong to you.

IN BRIEF

Quantum Cheshire cat experiment shows that two particles can exchange physical properties. **So-called weak** measurements are averaged over many testing runs, indicating the nature of the particles involved. **In a new version** of the test, photons are separated from their physical features, which are swapped, and the photons end up massively entangled.

The study claims to demonstrate this paradoxical disconnect between particles and their properties via a new version of the so-called quantum Cheshire cat experiment. First performed in 2013, the experiment draws its name from the disappearing feline in Lewis Carroll's *Alice's Adventures in Wonderland* and involves the ostensible separation of a cat (actually, a particle) from its grin (some property of the particle).

The new version of the experiment starts with two grinning Cheshire cats and ends with the grin of one cat gracing the other cat's face, and vice versa. In quantum terminology, it shows how two particles could end up exchanging their properties, or physical attributes.

"Niels Bohr's view [was] that until you do a measurement on a quantum system, you cannot say that the physical attribute actually exists. That questions the reality of physical attributes," says Arun Kumar Pati of the Harish-Chandra Research Institute (HRI) in India, who co-authored the work. "Our thought experiment takes that view a step ahead. Not only are the attributes not real, but they could not be yours. It questions the reality at a much deeper level."

THE WEAK VS. THE STRONG

TO ARRIVE AT THEIR CONCLUSION, Pati and his HRI colleague Debmalya Das resorted to a technique known as weak measurement.

In standard quantum mechanics, examining the state of a quantum system—such as a particle or an atom—involves a so-called strong measurement, which can be something as simple as a detector registering the arrival of a photon. A particle is first prepared in some initial state, a process called preselection. Then the quantum state of the particle evolves over time, under the influence of external forces, and it can end up in a superposition of many states. The strong measurement randomly "collapses" the superposition into one of those many possible states—a process that is unavoidably destructive. For example, if you were measuring the position of a photon, a strong measurement would locate the photon but also destroy the superposition.

Weak measurements, on the other hand, are not so heavy-handed. They represent an idea that goes back to 1988, to a theory devised by Yakir Aharonov, David Z. Albert and Lev Vaidman, all then at the University of South Carolina and Tel Aviv University. The trio asked,

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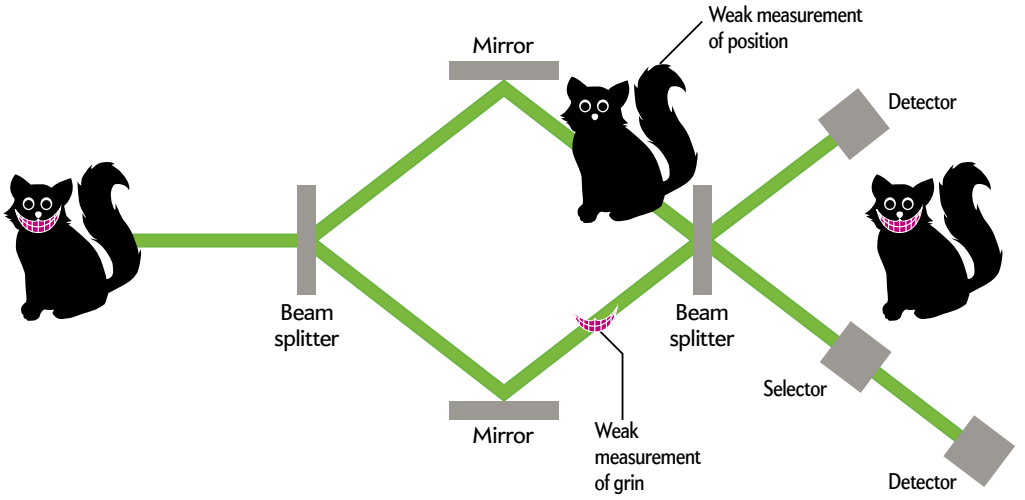
Creating a Quantum Cheshire Cat

Drawing its name from the disappearing feline in Lewis Carroll's *Alice's Adventures in Wonderland,* the quantum Cheshire cat experiment involves the separation of a "cat" (a particle) from its "grin" (some property of the particle). The canonical version of the experiment, first performed in 2013 and simplistically represented here, fired neutrons (a black cat) possessing a particular spin (a pink grin) through a system of optical elements that included an interferometer, beam splitters, mirrors and detectors. A carefully choreographed sequence of strong and weak measurements on the neutrons as they traversed the system yielded a paradoxical result, in which the neutrons passed through one of two paths while their spins were only observable in the other. In other words, the "cat" had been separated from its "grin."



MELISSA THOMAS BAUM *Buckyball Design;* SOURCE: "OBSERVATION OF A QUANTUM CHESHIRE CAT IN A MATTER-WAVE INTERFEROMETER EXPERIMENT" BY TOBIAS DENKMAYR ET AL., IN *NATURE COMMUNICATIONS,* VOL. 5; JULY 29, 2014

What if the measuring device interacted extremely weakly with the particle? While such a measurement would not destroy the quantum state (and thus the state would continue evolving), it would result in a value for the state with a very large uncertainty. If you performed the measurements over and over again, with an ensemble of identically prepared, or preselected, particles, then you would get a distribution of weak measurement values.

On its own, this distribution is not informative. But add one more stage to the process, and things get very interesting. After each weak measurement, you let the particle evolve and then perform a strong, destructive measurement on it. Repeat this action for every identically preselected, weakly measured particle. Each strong measurement will give a different value because of the random collapse of the superposition. Now select only those particles whose final positions have a certain value—doing so is called postselection. Then discard information about all of the particles that do not end up in this postselected stage. What Aharonov and his colleagues argued is that you can now take the weakly measured values for the subset of postselected particles and turn it into a "weak value" that tells you something about a property of the particles, such as their spin in a given direction.

An intriguing outcome of this approach to quantum systems has to do with the nature of time. According to the mathematics developed by Aharonov and his colleagues, weak values are influenced by both the initial preselected quantum state (the past) and the final postselected quantum state (the future). Time, in this way of thinking, flows both ways: the future influences the present.

WHOSE PROPERTY IS IT, ANYWAY?

IN A FIRST-OF-ITS-KIND experiment published in 2014, Tobias Denkmayr of the Vienna University of Technology, Jeff Tollaksen of Chapman University and their colleagues used weak measurements to separate the quantum Cheshire cat from its grin.

In their experiment, preselected neutrons with a particular spin were sent, one by one, into a beam splitter, which is a device that splits a beam of particles into two. Each incoming neutron ended up in a superposition of two states: taking paths A and B. These two paths were recombined in a so-called interferometer, which caused the quantum states to inter-

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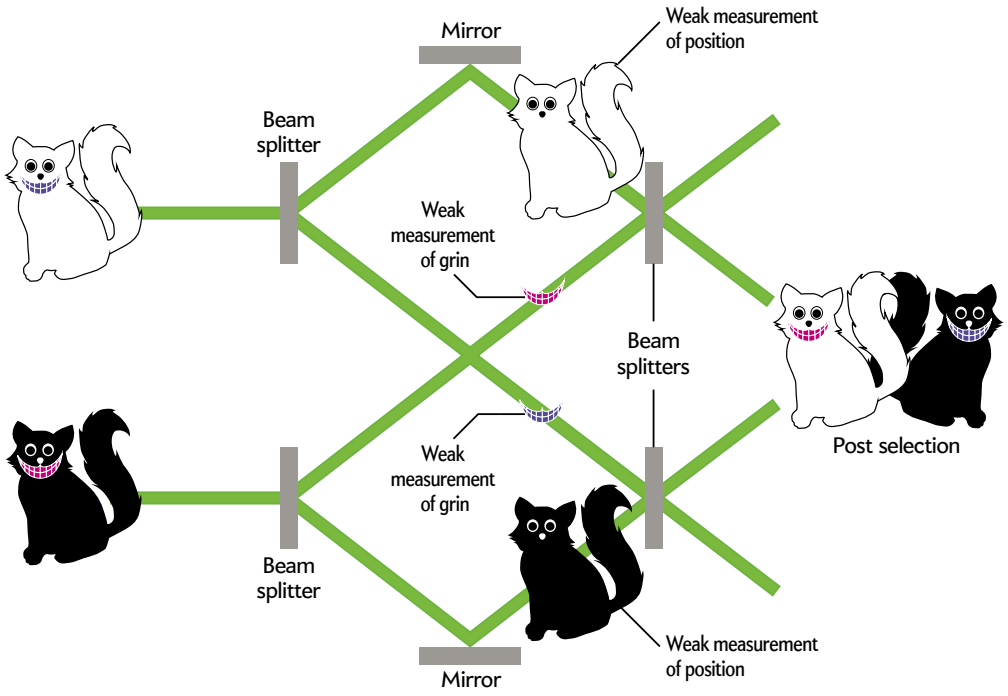
Two Quantum Cats Swap Grins

A newly proposed elaboration of the quantum Cheshire cat experiment calls for not only separating particles from their properties but also exchanging those properties between the particles. In other words, this version of the experiment would first strip away and then swap the grins of two quantum Cheshire cats. In this experiment, which crucially relies upon intermixing the outputs of not one but two interferometers before performing multiple strong and weak measurements, two photons (the white and the black cats) are decoupled from their polarizations (the blue and the pink grins). This illustration depicts the paths of the photons and their weakly measured polarizations through a schematic representation of the proposed optical system. The experiment's final result, its creators say, would be the exchange of polarization states and formation of a single entangled state between the two spatially separated photon



MELISSA THOMAS BAUM *Buckyball Design*; SOURCE: "CAN TWO QUANTUM CHESHIRE CATS EXCHANGE GRINS?" BY DEBMALYA DAS ET AL., IN ARXIV.ORG AT HTTPS://ARXIV.ORG/ABS/1904.07701; APRIL 14, 2019

fere. The neutrons then headed toward output detectors. In one of the output paths of the interferometer, the experiment involved a strong measurement of a particular spin state of the neutrons. Neutrons that satisfied this criterion were considered to be postselected. The experimenters discarded all of the other neutrons for their analysis.

For these postselected particles, the team also performed two sets of weak measurements: one for the position of the particles and the other for their spin. These dual measurements suggested that the particles were going through path B, whereas the weak value of their spin could be measured only in path A. The cat had been separated from its grin.

"From the old perspective of preparing a particle and then doing a strong measurement, it is impossible to separate a particle from its properties," says Tollaksen, who wrote about the Cheshire cat paradox in his 2001 Ph.D. thesis.

Now Pati and Das have extended the Cheshire cat experiment to their thought experiment, which not only separates a particle from its properties but also causes one particle to take on a property previously associated with another, and vice versa.

The thought experiment involves putting two interferometers side by side, such that each particle first encounters a beam splitter. After going through the beam splitter, the particle enters into a superposition of two states: taking the left and right paths.

Then comes a twist: The alignment of the setup is such that interferometer 1's right path, which would normally be recombined with its corresponding left path, is instead recombined with interferometer 2's right path. And the interferometers' left paths are

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recombined as well. When recombined, the various quantum states interfere with one another. Then the two outputs from each interferometer encounter a series of beam splitters and detectors. These beam splitters are designed to make photons with one type of polarization go one way and the rest go the other way. (Polarization describes the orientation of a photon's vibrating electric and magnetic fields.) The postselection involves choosing only those photons that cause a particular set of six detectors to click simultaneously. All other photons are discarded.

According to Pati and Das, if one were to calculate weak values for the position and polarization of each pair of photons in the postselected ensemble, then the weak values would show that photon 1 went through the left arm of interferometer 1, whereas its polarization would appear in the left arm of interferometer 2. Similarly, photon 2 would appear in the right arm of interferometer 2, whereas its polarization would show up in the right arm of interferometer 1. At least, that is how the researchers interpret the weak values.

This interpretation of the thought experiment suggests that after the particles and their properties are decoupled, and their paths are recombined and finally subjected to strong measurements, photon 1 ends up with the polarization of photon 2, and vice versa. The cats and their grins are first separated, and then the cats exchange grins. Also, the photons, despite being separated from their initial properties, all end up in one massive entangled state—meaning that they can only be described by a single global quantum state.

"It doesn't surprise me," says Tollaksen, who is used to the seeming paradoxes thrown up by weak measurements. But "it's very good work."

A DISAGREEMENT OVER DETAILS

EXPERIMENTALIST Aephraim Steinberg of the University of Toronto is also not surprised but for different reasons. He points out that an interaction between particles results in those particles getting entangled (as happens in Pati and Das's thought experiment), and this entanglement can lead to the particles swapping properties. Such swapping is the basis of a so-called SWAP gate, a well-studied operation used in quantum computing, Steinberg says. "It would indeed be interesting if they could swap their polarizations without ever interacting," he adds.

But Steinberg is more surprised, even concerned, by the new experiment's design. "It relies on two photons traversing a set of interferometers and then causing six different detectors to fire simultaneously. This is, of course, impossible," he says. "The authors seem to be imagining one detector sensitive to where a photon is, while another detector (at another location) could simultaneously measure the photon's polarization. In this sense, they seem to be trying to 'build in' the separation of the photon's different properties from the start rather than devising an experiment to reveal it."

Tollaksen also says that having six detectors firing simultaneously with only two photons is simply not possible. But he thinks Pati and Das's conceptual idea is sound. "As far as I can tell, it seems to me that even the requirement of all six [detectors] could be boiled back down to two with the right optics and still produce the right postselection," he says. "If so, the fundamental swapping idea they are playing with might be salvageable."

But Pati says that his and Das's experiment should work as designed—and with existing technology, too. "The detector clicks are for various degrees of freedom or attributes of the two photons," he says, thus allowing for six simultaneous detections.

There is also a bigger issue of whether the weak values obtained via weak measurements are telling us something about what is real. "In general, I think too much is made of the quantum Cheshire cat being a paradox," says theorist Michael Hall of the Australian National University. "Weak values are not the outcomes of individual measurements in general. They are only average values of many repeated measurements." Hall argues that such average values cannot be accorded the same status as the outcome of individual strong measurements.

Nevertheless, weak measurements are already being used for seemingly impossible applications. For example, if one selects the initial state and the postselected state of particles such that there is very little overlap between the two, then the percentage of particles that have to be thrown away because they are not postselected becomes very large. But for the very few that remain, the weak values can be extremely useful. John C. Howell of the University of Rochester and his colleagues have already used such weak values to measure displacements of about 14 femtometers, which is roughly the size of a uranium nucleus.

Concerns about Pati and Das's thought experiment notwithstanding, the debate over the meaning of weak values is also one over the correct theory for describing the quantum world, particularly the role of time. "You need to start thinking about the relevance of the future on the present. The property [of a particle] at any given moment of time is influenced by the future," Tollaksen says. "When you shift your thinking to that, then all of these things, like the Cheshire cat, are not at all surprising." SA

Anil Ananthaswamy is author of *The Edge of Physics, The Man Who Wasn't There* and, most recently, *Through Two Doors at Once: The Elegant Experiment That Captures the Enigma of Our Quantum Reality*

MORE TO EXPLORE

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THE COOLEST PHYSICS YOU'VE EVER HEARD OF

Ultracold atoms can simulate all sorts of quantum behavior

By Karmela Padavic-Callaghan

WHEN IT COMES TO FURTHERING OUR overall understanding of the physical world, ultracold quantum gases are awfully promising. As the famous physicist Richard Feynman argued, to fully understand nature, we need quantum means of simulation and computation. Ultracold atomic systems have, in the past 30 years, proven to be amazing quantum simulators. The number of applications for these systems as such simulators is nothing short of overwhelming, ranging from engineering artificial crystals to providing new platforms for quantum computing. In its brief history, ultracold atomic experimental research has enhanced physicists' understanding of a truly vast array of important phenomena.

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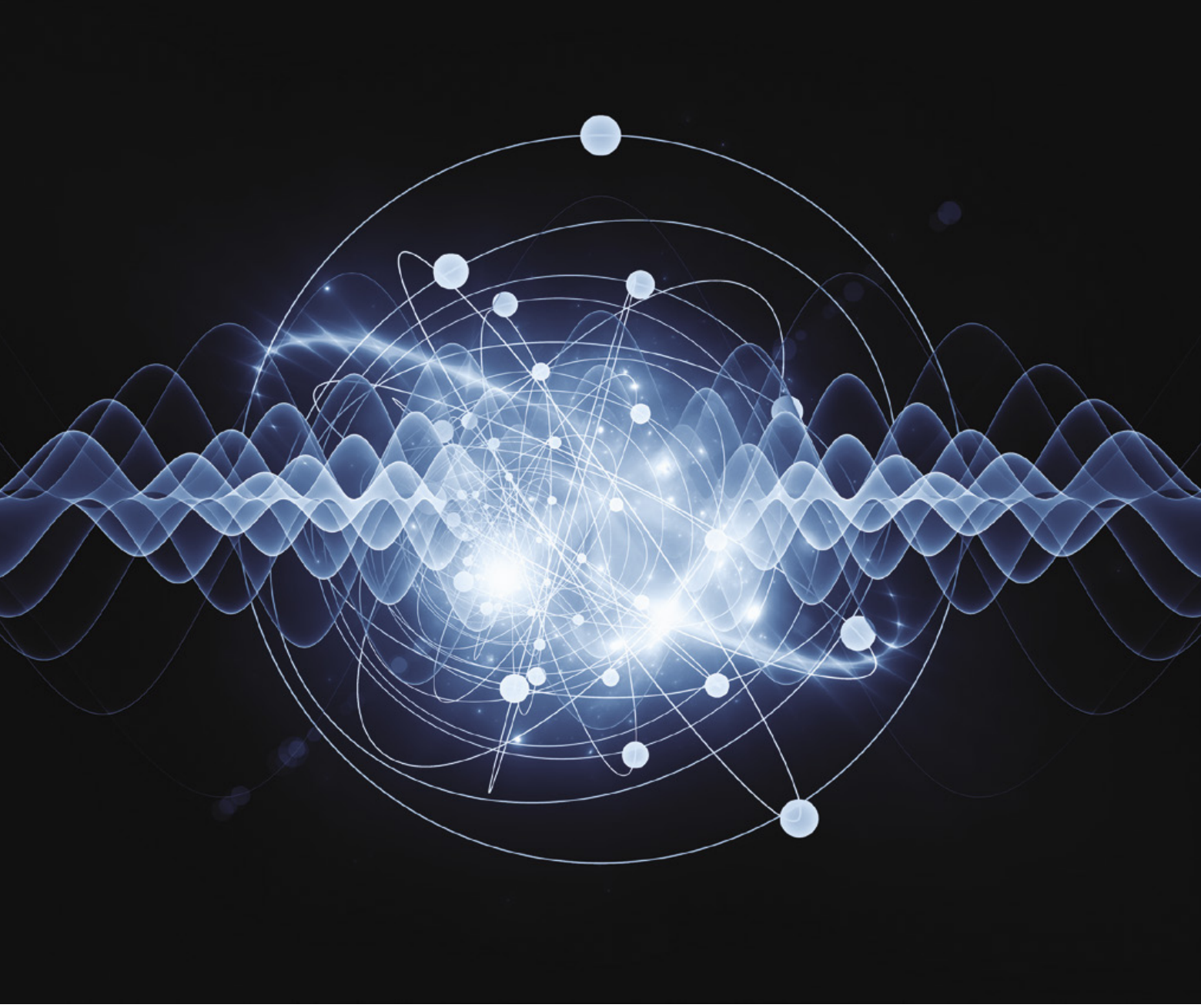

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One of the revelations of quantum mechanics is that any object can be seen as a wave (even you!) when an appropriate experimental test is used. Properties of these so-called matter waves depend on their temperature; at large temperatures they have short wavelengths and look and behave particlelike because all the peaks and valleys are so close together that they cannot be told apart. If we lower temperatures to much less than a single kelvin, the wave nature of matter becomes more pronounced and wavelike behaviors more important. What happens then with a large collection of very cold atoms that behave like a large collection of waves? They can all align and overlap to form a single wave, something that was historically called a macroscopic wave function. Such a system—a condensate in physics parlance—is a fundamentally quantum state of matter.

Quantum condensates were theoretically predicted in the mid-1920s, but it was only in the late 1990s that experimental physicists kicked off a revolution (recognized by two Nobel Prizes) by using lasers and magnets to reach sufficiently low temperatures for the transition to these phases of matter to happen. Light can interact with atoms and thus change their energies. Atoms also experience forces when placed in nonuniform magnetic fields. Physicists used these two properties to trap clouds of atoms such as rubidium and eventually lower their temperature to picokelvins—trillionths of a degree above absolute zero. Remarkably, experiments in which these extremely low temperatures can be reached, and quantum states of matter are engineered, fit in an average-sized room, on a large table with the ultracold atom gas frequently visible to the naked eye. The coldest places in the universe can often be found in a room on your local college campus, and they are likely controlled by a graduate student.

But it's not just making something the coldest or

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the most quantum that excites physicists; it's that ultracold atoms can be controlled and manipulated very precisely. Theoretical physicists have been especially emboldened by the possibility of engineering a quantum system by moving ultracold atoms around and fine-tuning the way in which they interact. To a theorist, a physical system such as a novel material that has some odd or unexpected property is a frustrating black box that is hard to describe with mathematical equations.

An ultracold atomic experiment can be the exact opposite, bringing equations to life and determining whether they measure up to nature. Many minimal, prototypical models, extensively studied at the level of mathematical equations but not necessarily matched by any naturally found material, can be engineered in ultracold atomic experiments. Since the late 1990s physicists of all sorts have embraced this idea and pushed it in every direction they could imagine.

As one example, adding counterpropagating laser beams to an ultracold atomic sample creates an optical lattice and turns the system into an artificial crystal. While a physical crystal has to be grown carefully, an ultracold artificial crystal can be changed from one shape to another by adjusting laser beams. Even more advantageously, such artificial crystals are typically very clean, and researchers can add in disorder by using more lasers. This means they can "reverse engineer" some of the effects of disorder. If a crystal is grown and then studied, it can be difficult to determine how much "dirt" in that sample actually matters for experimental outcomes. If researchers can control the disorder, then they can be very precise about determining its consequences.

ULTRACOLD ATOMIC SYSTEMS HAVE BEEN INVALUABLE FOR STUDYING HIGHLY INTERACTING MANY-BODY SYSTEMS, UNCOVERING PHENOMENA SUCH AS SYSTEMS FAILING TO REACH THERMAL EQUILIBRIUM AND NEVER LOSING "MEMORY" OF THEIR INITIAL STATE.

From the very first ultracold atomic experiments, they have been really important for studying fluids having zero viscosity or superfluids. When does a normal fluid become a superfluid? Can something similar to sound propagate through a superfluid? What happens if a container of superfluid is rotated? Many such fundamental questions have been answered through simulations with ultracold atoms.

For instance, rotating a superfluid has been predicted to give rise to the appearance of vortices—small hurricanes of quantum fluid—as a consequence of basic properties of the macroscopic wave function. Researchers are learning about quantum turbulence by observing and manipulating these vortices, thinking of them as controllable building blocks of more chaotic superfluid flows. Precise models for turbulent quantum flows have historically eluded theorists, which makes ultracold atomic simulations the first line of attack for this difficult problem.

As with studies of superfluids, many efforts have been made to simulate superconductors. They are perfect conductors having no resistance; no energy is wasted as electric current runs through them. As this is in contrast with all conductors used to supply electricity to businesses and households, it is a very active area of research to try and simulate a superconductor that does not have to be very cold. While a physicist's notion of "very cold" may not quite match the colloquial use of the phrase (a "cold atom" in physics jargon is vastly colder than a cold pint of ice cream in your fridge), even a few kelvins' worth of difference could be meaningful for applications of superconductors outside the lab.

Theoretical physicists have debated various high-temperature superconducting models for years, and ultracold atomic studies have been one of the prime ways to put those, sometimes conflicting, theories to test. Experimental physicists can also make a superfluid of ultracold atoms become something like a superconductor in a process called BEC-BCS crossover. This crossover has been theorized in semiconductors and neutron stars but never unequivocally confirmed in any system other than ones consisting of ultracold atoms.

Superconductors and superfluids are both fundamentally quantum phases of matter, making up something like a quantum expansion of the liquid-solid-vapor list of phases you may have learned in school. Ultracold atomic experiments continue to simulate even more novel quantum phases of matter. One striking example from 2019 is simulation of a quantum supersolid. A supersolid, like a superfluid, flows without any friction between the atoms that make it up, but also has a periodic, crystal-like structure like solids do. It is a seemingly paradoxical state of matter whose existence was debated for almost 50 years before ultracold atomic experiments provided a definitively affirmative conclusion.

Many so-called topological phases of matter have also been realized in ultracold systems. Some of these experiments simulate, and generalize, the quantum hall effect, which was first observed in more traditional experiments with semiconductors. Because many topological states of matter have properties unaffected by disorder, they are a very promising setting for quantum computation. In this way, realizing topological models in a very tunable ultracold atomic system means that physicists are not only able to simulate a new phase of matter but also immediately put it to

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use, getting closer to making a quantum computer.

Even if ultracold atomic systems have not been turned into quantum computation machines just yet, they can often be used to "beat" classical supercomputers in terms of enabling researchers to learn something new about fundamental physics. One example is that of many-body physics. In quantum mechanics, a system that has more than a few interacting particles is almost always a system where it is very difficult to calculate, and therefore predict, anything precisely. And yet real materials consist of millions of atoms!

Ultracold atomic systems have been invaluable for studying highly interacting many-body systems, uncovering phenomena such as systems failing to reach thermal equilibrium and never losing "memory" of their initial state. Physicists often resort to computational methods and supercomputers to study these systems, but a simulation with ultracold atoms can be a more direct way to attack some of their questions. Failure to equilibrate is of great interest in statistical physics, and the advent of ultracold atomic experiments has reinforced it as a very active field of contemporary physics research.

As for me personally, despite being trained in the broader discipline of condensed matter physics, I spent my six years as a graduate student coming back to ultracold atoms over and over again. Mostly I have been studying superfluid bubbles (hollow shells) made of ultracold atoms. This led me to the work of NASA scientists who launched an ultracold atom experiment into space to explore how it will be affected by extremely low gravity. This experiment is still ongoing onboard the International Space Station, and theorists like me who made predictions about what it will find are anxiously awaiting results.

In a way, it is fitting that studying hollow ultracold shells caused me to think about space, as part of the motivation for this research lies with neutron stars. Physicists don't really know what you would find if you could observe the inside of neutron star, but many theories suggest that it looks like an onion with layers of superconductors and superfluids. Studying superfluid shells in laboratories could then lead to a better understanding of some of these layers that reside in stars that are so far away that scientists may never be able to study them directly. Moreover, measurements of radio signals coming from neutron stars suggest that superfluid vortices within them may affect their rotation.

Ultracold atomic experiments have excelled in studying exactly those vortices with great precision. In the past few years, I have been working on mathematical arguments for what a vortex in a hollow shell of ultracold atoms might do if the whole thing started rotating. I have badgered a fair number of my experimental colleagues with questions about engineering such a system in their labs, and the fact that this is even something we can talk about, some semblance of simulating the quantum innards of a neutron star, still seems to me a little bit like science fiction.

My latest ultracold obsession came when I learned about quasiperiodicity in one-dimensional chains of ultracold atoms. The puzzle hiding behind the jargon is simple: physicists know well how structures of atoms in which they repeat with a regular period behave in nature, but what happens if that period is an irrational number? Such systems are called quasiperiodic, and studying them led cognitive scientist Douglas Hofstadter in 1976 to discover a famous fractal plot later dubbed as his butterfly. Hofstadter's plot is self-similar: if you zoom in or zoom out any amount, it still looks the same.

This property implies that physical states having fractional dimensions can exist in nature, a revelation that jump-started a search for more physical systems where that can happen. Two years ago another graduate student mentioned to me that they had simulated a quasiperiodic system in their ultracold atomic research lab, and I, too, have not stopped chasing the Hofstadter butterfly since. Why would nature care about the difference between rational and irrational numbers so much as to allow for fractional dimensions to be more than a mathematical oddity? Ultracold atomic studies are likely to help physicists answer that question, and I hope to be around to hear about them.

My experience as a researcher has included only a sliver of many topics in modern physics for which ultracold atomic experiments are meaningful. The possibilities are truly numerous. And the quantum simulation revolution is nowhere near over! Researchers continue to push the limits of existing technology to cool gases made up of more elements and execute more manipulations.

Next steps? Quantum chemistry, where molecules form at ultracold temperatures. Ultracold quantum systems that are so large they cannot be called microscopic despite quantum mechanics always being assumed to only describe the smallest of objects. Ultracold systems that can be used to measure fundamental constants in tabletop experiments instead of large accelerators (like the Large Hadron Collider). Ultracold experiments where a single atom can be poked, prodded, moved around and imaged. And whatever else can give us a window into the fundamentals of our (quantum) world. SA

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MORE TO EXPLORE

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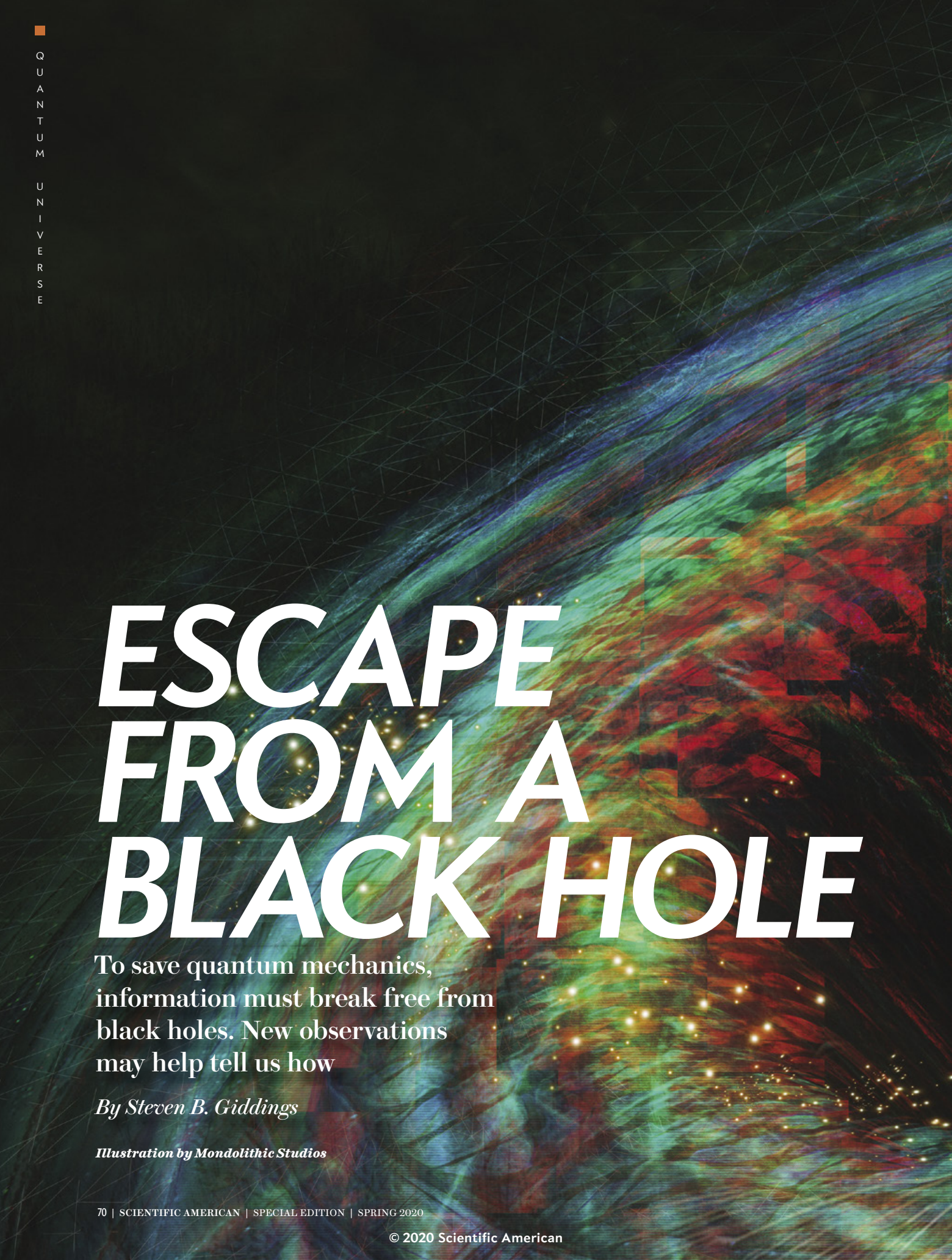

ESCAPE FROM A BLACK HOLE

To save quantum mechanics, information must break free from black holes. New observations may help tell us how

By Steven B. Giddings

Illustration by Mondolithic Studios

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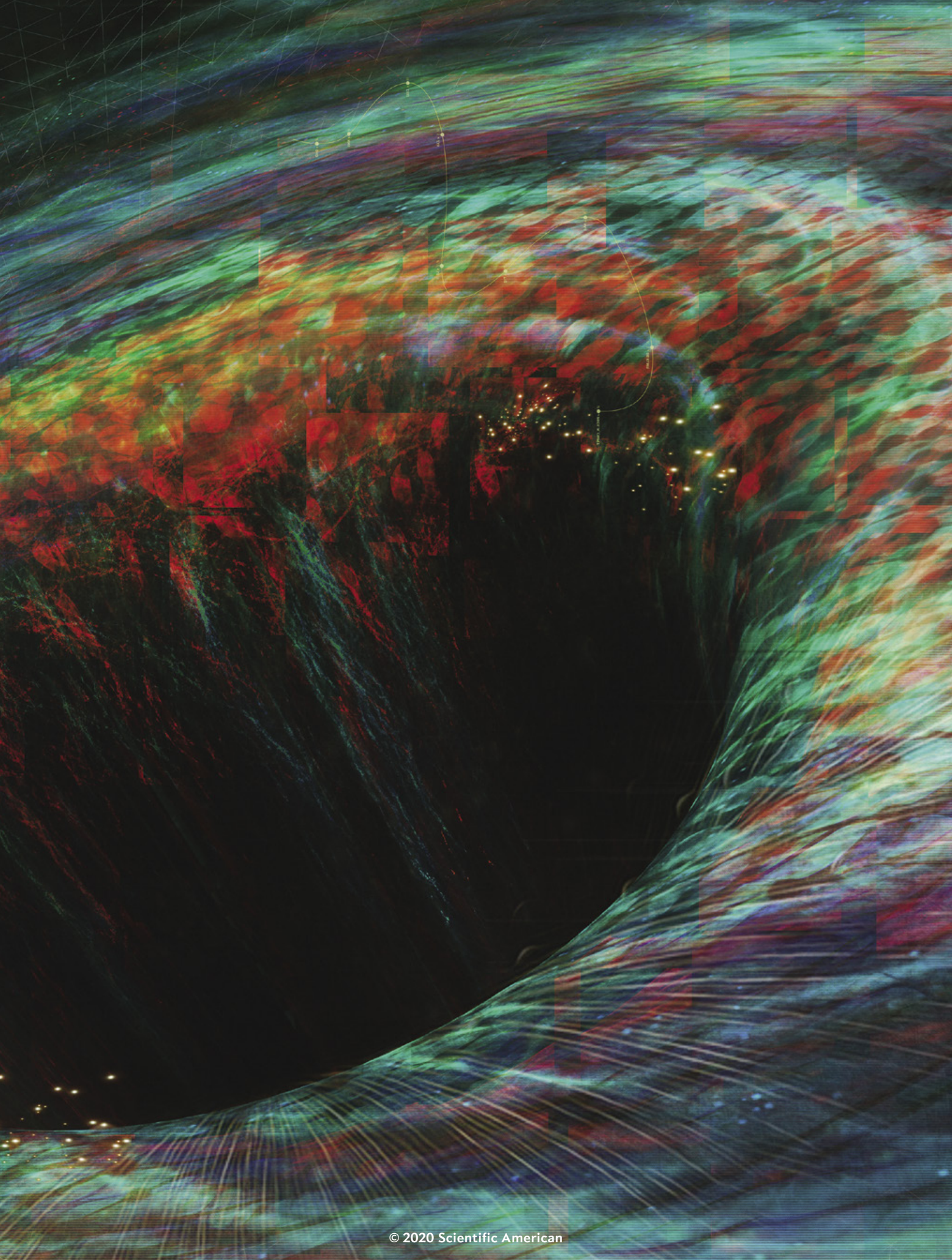

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HUMANKIND CAUGHT ITS FIRST GLIMPSE of a black hole on April 10, 2019. The Event Horizon Telescope (EHT) team, which uses an Earth-spanning network of radio observatories acting in concert, shared images it had captured of an apparent black hole with 6.5 billion times the mass of our sun in the center of the nearby M87 galaxy. This was a breathtaking achievement—our first view of one of the most mysterious objects in the universe, long predicted but never directly "seen." Even more exciting, the images, and the observations that should follow, are beginning to provide new clues about one of the deepest puzzles in physics.

This enigma is the "paradox" of what happens to information in a black hole. By investigating this question, physicists have discovered that the mere existence of black holes is inconsistent with the quantum-mechanical laws that so far describe everything else in our universe. Resolving this inconsistency may require a conceptual revolution as profound as the overthrow of classical physics by quantum mechanics.

Theorists have explored many ideas, but there has been little direct evidence to help resolve this problem. The first image of a black hole, however, begins to offer actual data to inform our theories. Future EHT observations—especially those that can show how black holes evolve over time—and recent detections of colliding black holes by gravitational-wave observatories could provide important new insights and help to usher in a whole new era of physics.

IN BRIEF

According to quantum mechanics, information can never be destroyed. But when combined with general relativity, quantum rules say that black holes destroy information. **Scientists have proposed** modifications to the classical picture of black holes that could solve the paradox, but they lack evidence to test them. **That is changing** with the new Event Horizon Telescope, which recently took the first picture of a black hole, as well as with gravitational-wave measurements of black holes colliding.

THE INFORMATION PROBLEM

THOUGH DEEPLY MYSTERIOUS, black holes seem to be ubiquitous in the cosmos. The EHT observations and the gravitational-wave measurements are just the latest and most robust evidence that black holes, despite sounding fantastical, do indeed appear to be real—and remarkably common. Yet their very existence threatens the present foundations of physics. The basic principles of quantum mechanics are thought to govern all the other laws of nature, but when they are applied to black holes they lead to a contradiction, exposing a flaw in the current form of these laws.

The problem arises from one of the simplest questions we can ask about black holes: What happens to stuff that falls into them? We need a little refinement here to fully explain. First, according to our present quantum-mechanical laws, matter and energy can shift between different forms: particles can, for example, change into different kinds of particles. But the one thing that is sacred and never destroyed is quantum information. If we know the complete quantum description of a system, we should always be able to exactly determine its earlier or later quantum description with no loss of information. So a more precise question is, What happens to quantum information that falls into a black hole?

Our understanding of black holes comes from Albert Einstein's general theory of relativity, which describes gravity as arising from the curvature of space and time; a common visualization of this idea is a heavy ball deforming the surface of a trampoline. This warping of spacetime causes the trajectories of massive bodies and light to bend, and we call that gravity. If mass is sufficiently concentrated in a small-enough vicinity, the nearby spacetime deformation is so strong that light itself cannot escape a region inside what we call the event horizon: we have a black hole. And if nothing can travel faster than light—including information—everything must get stuck inside this boundary. Black holes become cosmic sinkholes trapping information along with light and matter.

But the story becomes stranger. What may be Stephen Hawking's greatest discovery is his 1974 prediction that black holes evaporate. This finding also led to the startling idea that black holes destroy quantum information. According to quantum mechanics, pairs of "virtual particles" pop into existence all the time, everywhere. Typically such a pair, consisting of a particle and its antimatter counterpart, quickly annihilates, but if it forms near the horizon of a black hole, one particle might pop up inside this boundary and the other outside. The outside particle can escape, carrying away energy. The law of energy conservation tells us that the black hole has thus lost energy, so the emission of such particles causes the black hole to shrink over time until it completely disappears. The problem is that the escaping particles, known as Hawking radiation, carry essentially no information

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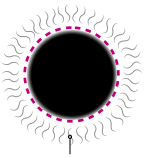
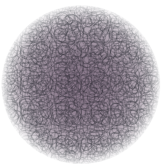
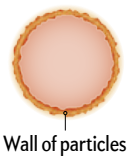
The Information Problem

Black holes were predicted by general relativity, and mounting astrophysical evidence supports their existence. But in 1974 Stephen Hawking argued that black holes eventually evaporate. If so, everything that falls into them is ultimately destroyed, including the information contained in the matter that fell in. The problem is that quantum mechanics and energy conservation forbid such destruction of information. In response, physicists have come up with several suggestions for how to modify our picture of black holes to make them compatible with quantum physics:

	HYPOTHESIS	DESCRIPTION	PROBLEM
Information is destroyed	**"Classical" black hole**	Black hole with an event horizon; information that enters the black hole is destroyed when the black hole evaporates.	Contradicts quantum mechanics and energy conservation, which say that information cannot be destroyed.
Information is not destroyed	**Soft hair** 	Information does not fully enter the black hole but instead leaves an "imprint" just outside the event horizon.	Most experts do not regard this picture as providing a convincing resolution.
	Fuzzball 	A type of massive remnant in which the black hole horizon is replaced by strings and higher-dimensional geometry.	All three of these scenarios require modification of the conventional notion of locality—that is, the idea that nothing, including information, can travel faster than light.
	Firewall 	A type of massive remnant in which a "wall" of high-energy particles replaces the horizon; there is no black hole interior.	
	Quantum halo	A quantum black hole interacts with its surroundings, possibly through small fluctuations in spacetime, allowing information to transfer out.	

about what went into the black hole. Therefore, Hawking's calculations appear to show that quantum information that falls into a black hole is ultimately destroyed—contradicting quantum mechanics.

This revelation initiated a deep crisis in physics. Great advances have followed from previous such crises. For instance, at the beginning of the 20th century, classical physics seemed to predict the inevitable instability of atoms, in obvious contradiction to the existence of stable matter. That problem played a key role in the quantum revolution. Classical physics implied that because orbiting electrons within atoms are constantly changing direction, they continually emit light, causing them to lose energy and spiral into the nucleus. But in 1913 Niels Bohr proposed that electrons actually travel only within quantized orbits and cannot spiral in. This radical idea helped to establish the basis of quantum mechanics, which fundamentally rewrote the laws of nature. Increasingly it seems that the black hole crisis will similarly lead to another paradigm shift in physics.

QUANTUM ALTERNATIVES

WHEN HAWKING FIRST predicted black hole evaporation, he suggested that quantum mechanics must be wrong and that information destruction is allowed. Yet physicists soon realized this change would require a drastic breakdown of the law of energy conservation, which would disastrously invalidate our present description of the universe. Apparently the resolution must be sought elsewhere.

Another early idea was that black holes do not completely evaporate but instead stop shrinking at a tiny size, leaving behind microscopic remnants containing the original information. But, scientists realized, if this were true, basic properties of quantum physics would predict catastrophic instabilities causing ordinary matter to explode into such remnants, also contradicting everyday experience.

Obviously something is deeply wrong. It is tempting to conclude that the flaw is in Hawking's original analysis and that somehow information does escape a black hole emitting Hawking radiation. The challenge here is that this scenario would conflict with a foundational concept of present-day physics, the principle of locality, which states that information cannot move from one place to another superluminally—that is, faster than the speed of light. But according to our definition of black holes, the *only* way to escape one is to travel faster than light, so if information does escape, it must be doing so superluminally, in conflict with locality. In the four decades since Hawking's discovery, physicists have tried to find a loophole to this argument that stays within conventional physics, but none has emerged.

The closest attempt was a 2016 proposal by Hawking, Malcolm Perry and Andrew Strominger, who suggested that a mistake in the original analysis implies information never fully enters a black hole but

Illustration by Amanda Montañez

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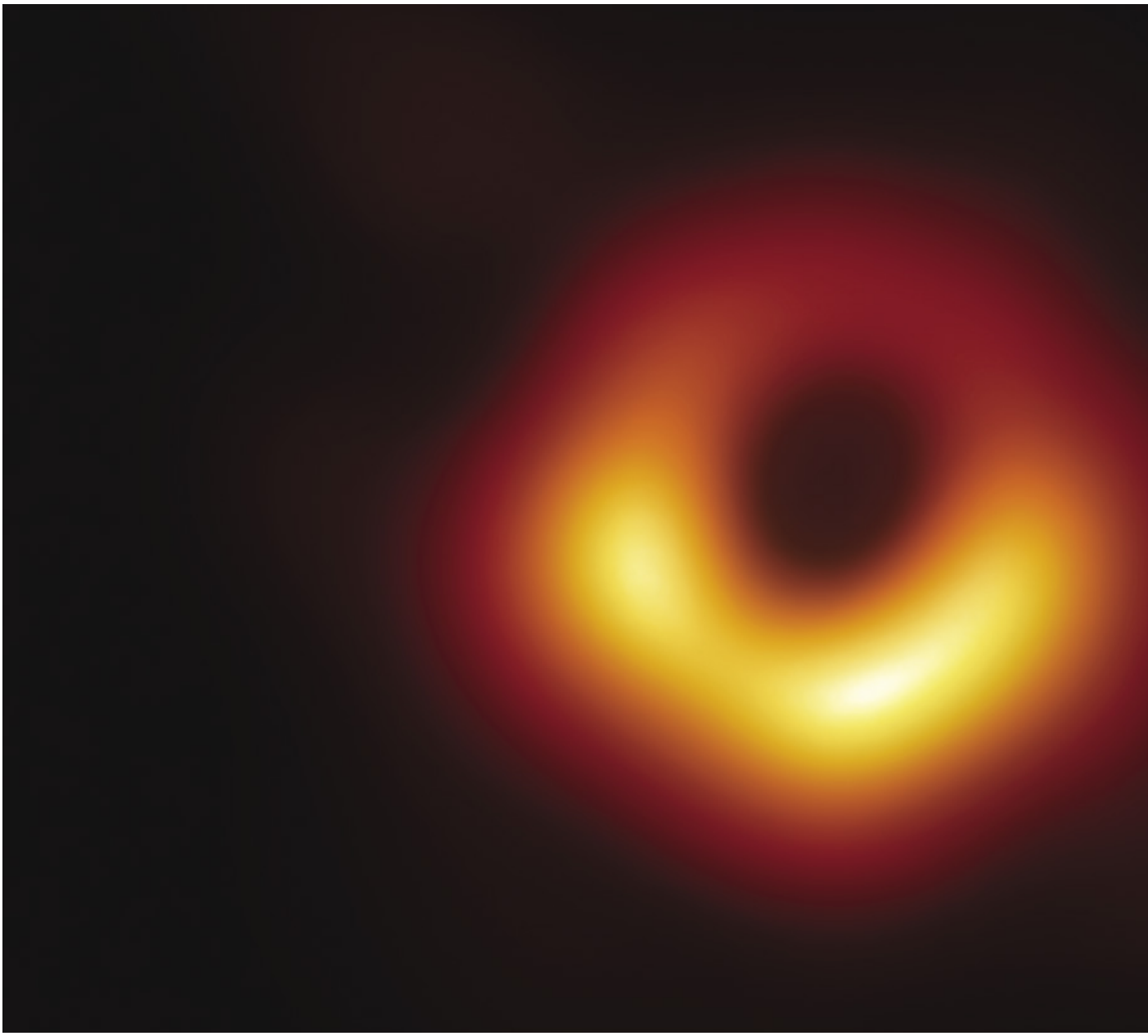

GRAVITY BENDS light around an apparent black hole at the center of the M87 galaxy in this seminal image from the Event Horizon Telescope.

EHT COLLABORATION AND EUROPEAN SOUTHERN OBSERVATORY

instead leaves a kind of imprint in the form of what they called "soft hair" outside it. Closer examination seems to be closing this loophole, however, and most experts do not believe this can be the answer. In short, more radical steps appear to be needed.

An obvious idea is that there is some unknown physics that prevents true black holes from existing at all. The conventional picture of black hole formation says that when very large stars burn out and die, their mass collapses under the force of gravity into a black hole. But what if they never reach that stage and actually transform into objects with "better" behavior? In fact, we know that when lower-mass stars such as our sun burn out and collapse, they do not form black holes and instead form dense remnants—for example, white dwarfs or neutron stars. Perhaps some unknown laws of physics also prevent larger stars from forming black holes and instead lead them to become a kind of "massive remnant"—something more like a neutron star than a black hole.

The problem with this suggestion is that we cannot explain what would stabilize such objects—no known physics should prevent their continued collapse under gravity, and any imagined physics that did would apparently require superluminal signaling from one side of the collapsing matter to the other. In fact, conventional large black holes can form from *very* low-density matter. To illustrate, if the 6.5-billion-solar-mass black hole in M87 arose from the collapse of a dust cloud (which is theoretically possible, although the actual process was apparently more complex), it would have happened when the dust

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reached the density of air at the top of Mount Everest. (Air on top of Everest does not form a black hole, because there is not enough of it; one would require an accumulated 6.5 billion solar masses.) Some drastic and superluminal new physical process would need to take over in such a low-density regime to instantly convert the collapsing cloud into a massive remnant instead of allowing a black hole to form.

A related idea is that something could cause black holes to change into massive remnants containing the original information after they form but long before they evaporate. But once again, this story requires nonlocal transfer of information from the interior of the initial black hole to the final remnant.

Despite their problems, physicists have explored versions of both these scenarios. For example, in 2003 Samir Mathur put forward a proposal based on string theory, which posits that fundamental particles are tiny strings. His idea is that a black hole transforms into a "fuzzball," a kind of massive remnant, or that a fuzzball forms instead of a black hole in the first place. Thanks to the complicated physics of string theory and its allowance for more than the traditional four dimensions of spacetime, fuzzballs might have a complex higher-dimensional geometry; instead of the sharp traditional boundary of a black hole at the event horizon, a fuzzball would have a fuzzier and larger boundary where one encounters strings and higher-dimensional geometry.

Alternatively a more recent version of a remnant scenario is the proposal that instead of a black hole with an event horizon, a massive remnant forms with a surface "firewall" of high-energy particles where the horizon would be. This firewall would incinerate anything that encountered it, turning it into pure energy that added to the firewall. Both the firewall and the fuzzball, though, share the problem of needing locality violation, and the resulting objects would have other properties that are very hard to explain.

MODIFYING LOCALITY

A COMMON THREAD in massive-remnant proposals is that saving quantum mechanics appears to require violation of the locality principle. But doing so carelessly is expected to be as disastrous as modifying quantum mechanics and, in fact, typically leads to another paradox. Specifically, the laws of relativity say that if you send a faster-than-light signal in empty, flat space, observers traveling past you at a high-enough speed will see the signal going backward in time. The paradox arises because this superluminal signaling then allows you to send a message into your past, for example, asking someone to kill your grandmother before your mother is born.

Even though this kind of answer appears to contradict fundamental physical principles, it is worth a closer look. Modifying locality seems crazy, but we have not found an alternative that does not. The severe nature of the black hole crisis strongly suggests a resolution via some subtle violation of the locality principle, one that does not produce such paradoxes. Put differently, quantum mechanics implies information is never destroyed, so information that falls into a black hole *must* ultimately escape, possibly through some new, subtle "delocalization" of information that might become clear when we can finally find a way to unify quantum mechanics and gravity—one of the most profound problems of present-day physics. In fact, we have other reasons to think such a subtlety could be present. The very idea of localized information—that it can exist in one place and not in another—is more delicate in theories that include gravity than in those that do not, because gravitational fields extend to infinity, complicating the concept of localization.

If information does escape black holes, it might not

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require a change as obvious and abrupt as the formation of a massive remnant, whether fuzzball, firewall or another variant. The growing evidence for black holes suggests there are objects in the universe that look and act a lot like classical black holes, without large departures from Einstein's predictions. Is Einstein's general relativity so drastically wrong in its description of black holes, or might there be some more innocuous, currently unknown effects that delocalize information and allow it to leak from black holes, avoiding such a dramatic failure of the entire spacetime picture?

In my recent theoretical work, I have found two versions of such effects. In one, the geometry of spacetime near a black hole is altered, making it bend and ripple in a way that depends on the information in the black hole—but gently, so that it does not, for example, destroy an astronaut falling through the region where the horizon would ordinarily be found. In this "strong, nonviolent" scenario, such shimmering of spacetime can transfer the information out. Interestingly, I have also found that there is a subtler, intrinsically quantum way for information to escape the black hole. In this "weak, nonviolent" scenario, even tiny quantum fluctuations of the spacetime geometry near the black hole can transfer information to particles emanating from the hole. The fact that the information transfer is still large enough to save quantum mechanics is related to the huge amount of possible information a black hole can contain. In either picture, a black hole effectively has a "quantum halo" surrounding it, where interactions pass information back to its surroundings.

OUR VERY NOTIONS OF SPACE AND TIME, WHICH UNDERLIE THE REST OF SCIENCE, APPEAR TO REQUIRE SIGNIFICANT REVISION.

Notably, these scenarios, despite appearing to require superluminal travel of information, do not necessarily produce a grandmother paradox. The information signaling here is tied to the existence of the black hole, which has a spacetime geometry that is different from that of flat space, so that the earlier argument about communicating with the past no longer holds. These possibilities are tantalizing from another perspective: the locality principle is also what prohibits our own faster-than-light travel; the quantum mechanics of black holes seems to be telling us there is something wrong with the present formulation of this principle.

REWRITING THE LAWS OF PHYSICS

SO FAR SUCH A QUANTUM-HALO scenario has not been predicted by a more complete theory of physics that reconciles quantum mechanics with gravity, but it is strongly indicated by the need to resolve the problem and by assumptions based on what we see. If such a scenario is correct, it probably represents an approximate description of a deeper reality. Our very notions of space and time, which underlie the rest of science, appear to require significant revision. The present work to understand black holes may be akin to the first attempts to model the physics of the atom by Bohr and others. Those early atomic descriptions were also approximate and only later led to the profound theoretical structure of quantum mechanics. Although modifying locality seems crazy, we might find solace by noting that the laws of quantum mechanics also seemed very crazy to the classical physicists grappling with their discovery.

Given the immense challenge in sorting out the story of quantum black holes and the more complete theory describing them, physicists are eager for experimental and observational evidence to help guide us. The exciting recent advances have given humankind two direct observational windows on black hole behavior. In addition to the EHT's images of black holes, the Laser Interferometer Gravitational-wave Observatory (LIGO) and its companion facilities have begun to detect gravitational waves from collisions between apparent black holes. These waves carry valuable information with them about the properties and behavior of the objects that created them.

From a naive viewpoint, it seems preposterous that the EHT or LIGO could detect any departure from Einstein's description of black holes. Traditionally his theory has been expected to need modification only when spacetime curvatures become extremely large, near the center of a black hole; in contrast, curvatures are very weak near the horizon of a large black hole. But the information crisis I have described suggests otherwise. A large part of the theoretical community has now reached the consensus that some changes to the current laws of physics are needed to describe phenomena not just deep inside a black hole but all the way out past the horizon. We appear to have crossed the Rubicon. For the case of the black hole in M87, the distance at which we expect to find deviations from classical predictions is several times the size of our solar system.

Already LIGO and the EHT have ruled out wilder possibilities that could be considered in an attempt to give a logically consistent description of black holes. Specifically, if black holes were replaced by massive remnants more than about twice the diameter of the supposed black hole, we would have seen signs in the data from both experiments. In the case of the EHT, much of the light that produced the now famous image comes from a region around one and a half times the diameter of the event horizon. And for LIGO, part of the gravitational-wave signal that we detect is likewise produced from the region where

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the colliding objects reach similarly small separations. Although study of these signals is still in early phases, the EHT and LIGO have revealed very dark and very compact objects that produce signals just like those predicted for unmodified black holes.

Still, it is important to investigate these signals more closely. Sufficiently careful analysis might in fact uncover more clues about the quantum physics of black holes. Even if no new effects are observed, we then have information that constrains possible descriptions of their quantum behavior.

Sufficiently large-diameter remnants are now ruled out, but what about remnant scenarios that modify the black hole description only very near the horizon? Although a complete discussion would require a fuller theory of these remnants—such as fuzzballs or firewalls—we have some initial indicators. Specifically, if these objects had radii barely larger than the radius of the corresponding black hole horizon, then it is likely that neither EHT nor LIGO observations would be able to reveal such a structure because very little light or gravitational radiation escapes from the region very near the horizon.

One possible exception is the possibility of gravitational "echoes." As first suggested in 2016 by Vitor Cardoso of the University of Lisbon, Edgardo Franzin of the University of Barcelona and Paolo Pani of Rome University, if two such remnants combine to form a final remnant that has similar properties, gravitational waves can reflect off the merged remnant's surface and might be observed. Whereas most near-horizon scenarios are hard to rule out through observation, however, it is difficult to explain how such structures could be stable, instead of collapsing under their own weight to form black holes. Of course, this is a general problem for all massive-remnant scenarios, but it becomes even more challenging in the presence of the extreme forces in such a collision.

Prospects are better for testing some of the scenarios where new interactions behave like subtle modifications of spacetime geometry but extend well outside the horizon. For example, in the strong, nonviolent scenario, the rippling of a black hole's quantum halo can distort light passing near the black hole. If this scenario is correct, the shimmering could cause distortions of the EHT's images that change with time.

In my work with EHT scientist Dimitrios Psaltis, we found these changes could happen over roughly an hour for the black hole in the center of our galaxy. Because the EHT combines multihour observations into an average, such effects may be hard to see. But the relevant fluctuation time for the black hole in M87, which is more than 1,000 times larger, is more like tens of days. This work suggests we should look for these distortions by using longer-duration EHT observations than the project's initial seven-day span. If the experiment found such distortions, they would be a spectacular clue to the quantum physics of black holes. If they do not appear, that will begin to point to the subtler weak quantum scenario or to something even more exotic.

The weak, nonviolent scenario is harder to test because of the relative smallness of the expected changes to the geometry. Yet preliminary investigation shows that this scenario can alter how gravitational waves are absorbed or reflected, possibly yielding an observable modification to gravitational-wave signals.

If either scenario is correct, we will learn more not only about what quantum black holes are but also about the deeper laws of nature. Right now we do not fully understand how to think about information localization when gravitational fields are present. Quantum physics suggests that spacetime itself is not a fundamental part of physics but instead arises only as an approximation of a more basic mathematical structure. Evidence for quantum black hole effects could help make this concept more concrete.

To learn more, it is important to extend and improve both EHT and gravitational-wave measurements. For the EHT, it would be useful to have significantly longer-duration observations, as well as images of other targets such as our galaxy's central black hole, both of which are anticipated. For gravitational waves, more observations with increased sensitivity would be helpful and will be assisted when additional detectors come online in Japan and India, adding to the existing facilities in the U.S. and Europe. Furthermore, a strong complementary theoretical effort is needed to refine scenarios, to better clarify their origins and explanations, and to assess more thoroughly the question of how significantly they can affect EHT or gravitational-wave signals.

Whatever the resolution to the crisis, black holes contain crucial clues to the basic quantum physics of gravity, as well as to the very nature of space and time. Just as with the atom and quantum mechanics, a better understanding of black holes is likely to help guide the next conceptual revolution in physics. EHT and gravitational-wave observations have the potential to provide us with key information, either by ruling out quantum black hole scenarios or by discovering new phenomena associated with them. SA

Steven B. Giddings is a quantum physicist at the University of California, Santa Barbara, who focuses on high-energy theory, quantum aspects of gravity and quantum black holes.

MORE TO EXPLORE

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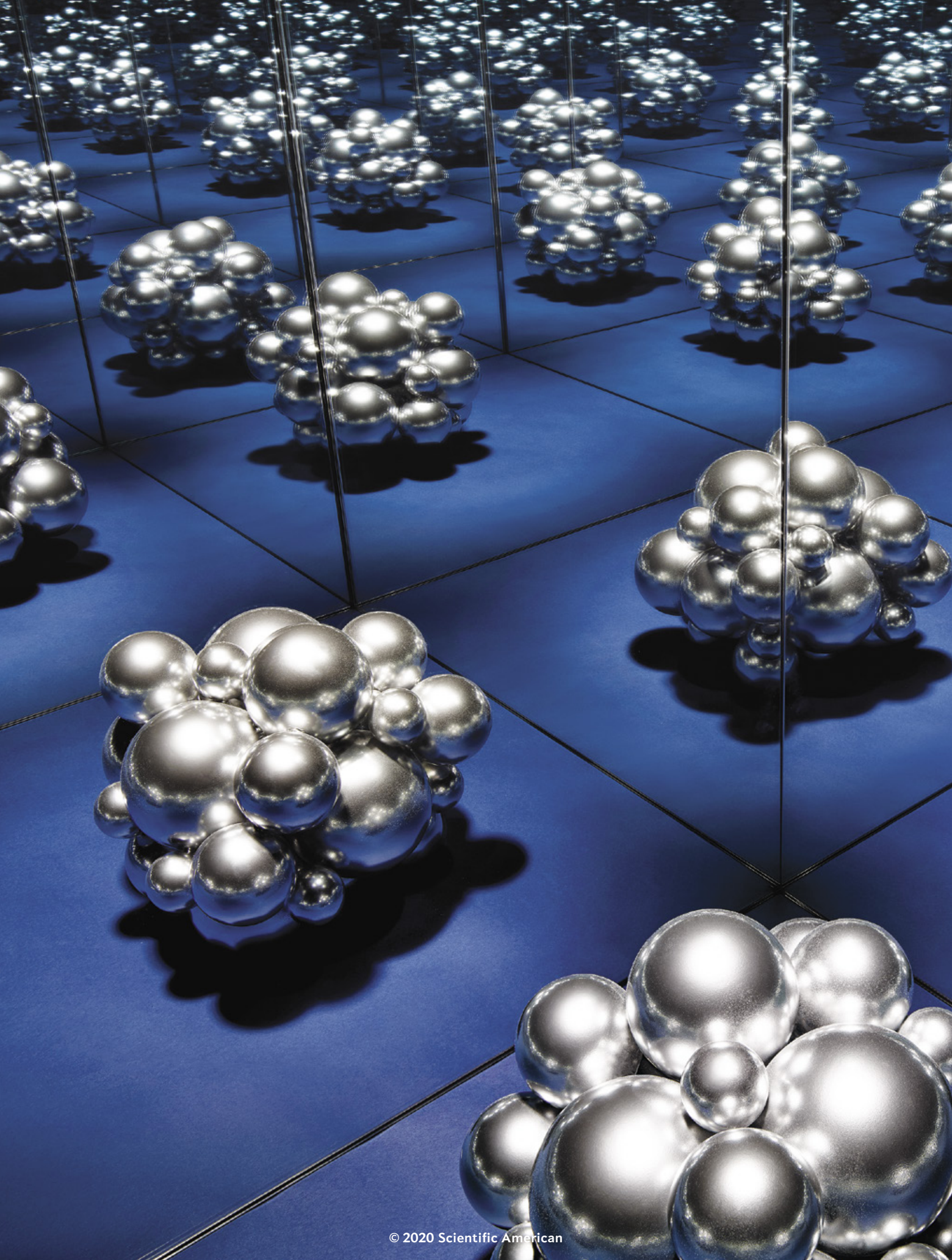

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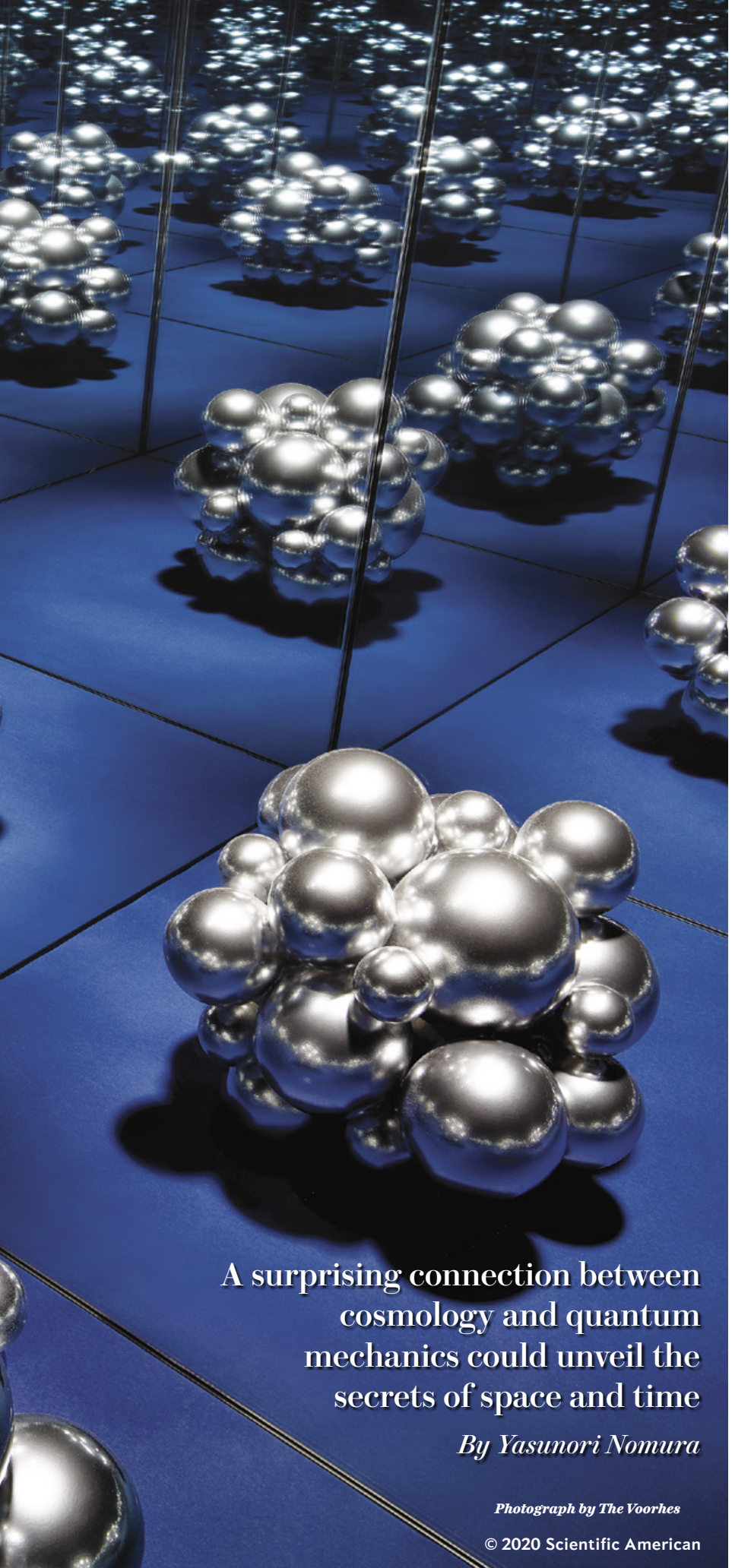
THE QUANTUM MULTIVERSE



A surprising connection between cosmology and quantum mechanics could unveil the secrets of space and time

By Yasunori Nomura

Photograph by The Voorhes

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MANY COSMOLOGISTS NOW ACCEPT THE EXTRAORDINARY IDEA THAT what seems to be the entire universe may actually be only a tiny part of a much larger structure called the multiverse. In this picture, multiple universes exist, and the rules we once assumed were basic laws of nature take different forms in each; for example, the types and properties of elementary particles may differ from one universe to another. The multiverse idea emerges from a theory that suggests the very early cosmos expanded exponentially. During this period of "inflation," some regions would have halted their rapid expansion sooner than others, forming what are called bubble universes, much like bubbles in boiling water. Our universe would be just one of these bubbles, and beyond it would lie infinitely more.

The idea that our entire universe is only a part of a much larger structure is, by itself, not as outlandish as it sounds. Throughout history scientists have learned many times over that the visible world is far from all there is. Yet the multiverse notion, with its unlimited number of bubble universes, does present a major theoretical problem: it seems to erase the ability of the theory to make predictions—a central requirement of any useful theory. In the words of Alan Guth of the Massachusetts Institute of Technology, one of the creators of inflation theory, "in an eternally inflating universe, anything that can happen will happen; in fact, it will happen an infinite number of times."

In a single universe where events occur a finite number of times, scientists can calculate the relative probability of one event occurring versus another by comparing the number of times these events happen. Yet in a multiverse where everything happens an infinite number of times, such counting is not possible, and nothing is more likely to occur than anything else. One can make any prediction one wants, and it is bound to come true in some universe, but that fact tells you nothing about what will go on in our specific world.

This apparent loss of predictive power has long troubled physicists. Some researchers, including me, have now realized that quantum theory—which, in contrast to the multiverse notion, is concerned with the very smallest particles in existence—may, ironically, point the way to a solution. Specifically, the cosmological picture of the eternally inflating multiverse may be mathematically equivalent to the "many worlds" interpretation of quantum mechanics, which attempts to explain how particles can seem to be in many places at once. As we will see, such a connection between the theories not only solves the prediction problem, it may also reveal surprising truths about space and time.

QUANTUM MANY WORLDS

I CAME TO THE IDEA of a correspondence between the two theories after I revisited the tenets of the many-worlds interpretation of quantum mechanics. This concept arose to make sense of some of the stranger aspects of quantum physics. In the quantum world—a nonintuitive place—cause and effect work differently than they do in the macro world, and the outcome of any process is always probabilistic. Whereas in our macroscopic experience, we can predict where a ball will land when it is thrown based on its starting point, speed and other factors, if that ball were a quantum particle, we could only ever say it has a certain chance of ending up here and another chance of ending up there. This probabilistic nature cannot be avoided by knowing more about the ball, the air currents or such details; it

IN BRIEF

The theory of cosmic inflation, which implies that the early cosmos expanded exponentially, suggests that we live not in a universe but a vast multiverse. **The problem with the multiverse idea,** however, is that all events that can occur will occur infinitely many times, ruining the theory's predictive ability. **Physicists realized** they can resolve the issue by viewing the multiverse as equivalent to a notion from quantum mechanics called the many-worlds interpretation, which suggests that our universe is one of many that coexist in "probability space" rather than in a single real space.

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NASA, ESA, S. BECKWITH (STScI) AND HUBBLE DEEP FIELD TEAM

HUBBLE SPACE TELESCOPE'S Ultra Deep Field shows galaxies as far away as 13 billion light-years. Objects much farther out will forever be beyond reach because the expansion of space causes them to recede faster than the speed of light. This so-called cosmological horizon has important implications for the theory of the multiverse.

is an intrinsic property of the quantum realm. The same exact ball thrown under the same exact conditions will sometimes land at point A and other times at point B. This conclusion may seem strange, but the laws of quantum mechanics have been confirmed by innumerable experiments and truly describe how nature works at the scale of subatomic particles and forces.

In the quantum world, we say that after the ball is thrown, but before we look for its landing spot, it is in a so-called superposition state of outcomes A and B—that is, it is neither at point A nor point B but located in a probabilistic haze of *both* points A and B (and many other locations as well). Once we look, however, and find the ball in a certain place—say, point A—then anyone else who examines the ball will also confirm that it sits at A. In other words, before any quantum system is measured, its outcome is uncertain, but afterward all subsequent measurements will find the same result as the first.

In the conventional understanding of quantum mechanics, called the Copenhagen interpretation, scientists explain this shift by saying that the first measurement changed the state of the system from a superposition state to the state A. But although the Copenhagen interpretation does predict the outcomes of laboratory experiments, it leads to serious difficulties at the conceptual level. What does the "measurement" really mean, and why does it change the state of the system from a superposition of possibilities to a single certainty? Does the change of state occur when a dog or even a fly observes the system? What about when a molecule in the air interacts with the system, which we expect to be occurring all the time yet which we do not usually treat as a measurement that can interfere with the outcome? Or is there some special physical significance in a human consciously learning the state of the system?

In 1957 Hugh Everett, then a graduate student at Princeton University, developed the many-worlds interpretation of quantum mechanics that beautifully addresses this issue—although at the time many received it with ridicule, and the idea is still less favored than the Copenhagen interpretation. Everett's key insight was that the state of a quantum system reflects the state of the *whole* universe around it, so that we must include the observer in a complete description of the measurement. In other words, we cannot consider the ball, the wind and the hand that throws it in isolation—we must also include in the fundamental description the person who comes along to inspect its landing spot, as well as everything else in the cosmos at that time. In this picture, the quantum state after the measurement is still a superposition—not just a superposition of two landing spots but of two entire worlds! In the first world, the observer finds that the state of the system has changed to A, and therefore any observer in this particular world will obtain result A in all subsequent measurements. But when the measurement was made, another universe split off from the first in

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Inflation Meets Many Worlds

The theory of inflation suggests that our universe is one of infinitely many that formed when the very early cosmos expanded exponentially. This picture of a multiverse, however, seems to destroy the theory's ability to make predictions because anything that can happen in an infinite multiverse will happen infinitely many times. The problem is solved, however, if the inflationary multiverse is equivalent to the "many worlds" interpretation of quantum mechanics, which posits that all these infinite universes coexist not in a single real space but in "probability space."

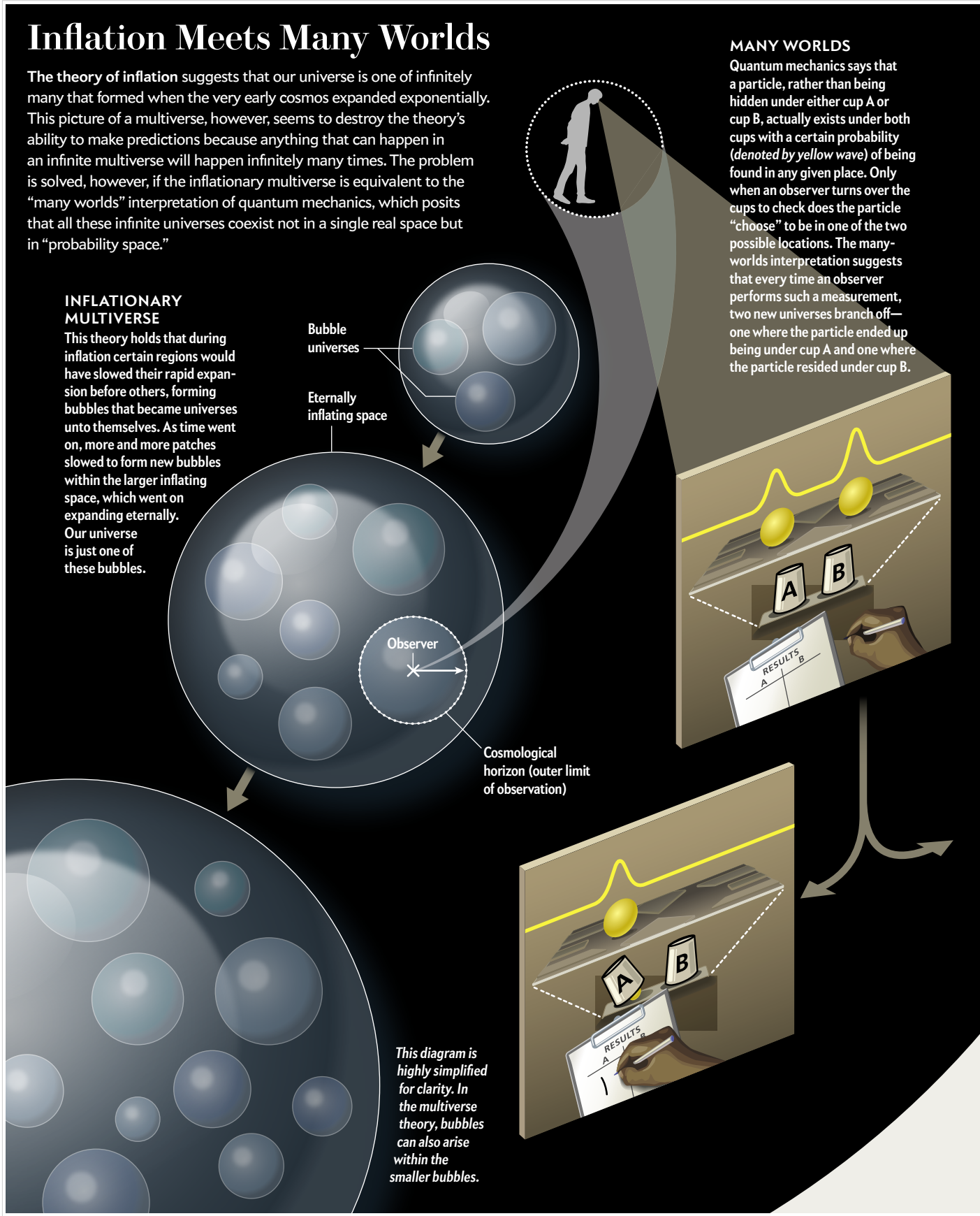
MANY WORLDS
Quantum mechanics says that a particle, rather than being hidden under either cup A or cup B, actually exists under both cups with a certain probability (*denoted by yellow wave*) of being found in any given place. Only when an observer turns over the cups to check does the particle "choose" to be in one of the two possible locations. The many-worlds interpretation suggests that every time an observer performs such a measurement, two new universes branch off—one where the particle ended up being under cup A and one where the particle resided under cup B.
INFLATIONARY MULTIVERSE
This theory holds that during inflation certain regions would have slowed their rapid expansion before others, forming bubbles that became universes unto themselves. As time went on, more and more patches slowed to form new bubbles within the larger inflating space, which went on expanding eternally. Our universe is just one of these bubbles.
Bubble universes
Eternally inflating space
Observer
Cosmological horizon (outer limit of observation)
A
B
RESULTS
A
B
This diagram is highly simplified for clarity. In the multiverse theory, bubbles can also arise within the smaller bubbles.

Illustration by Jen Christiansen

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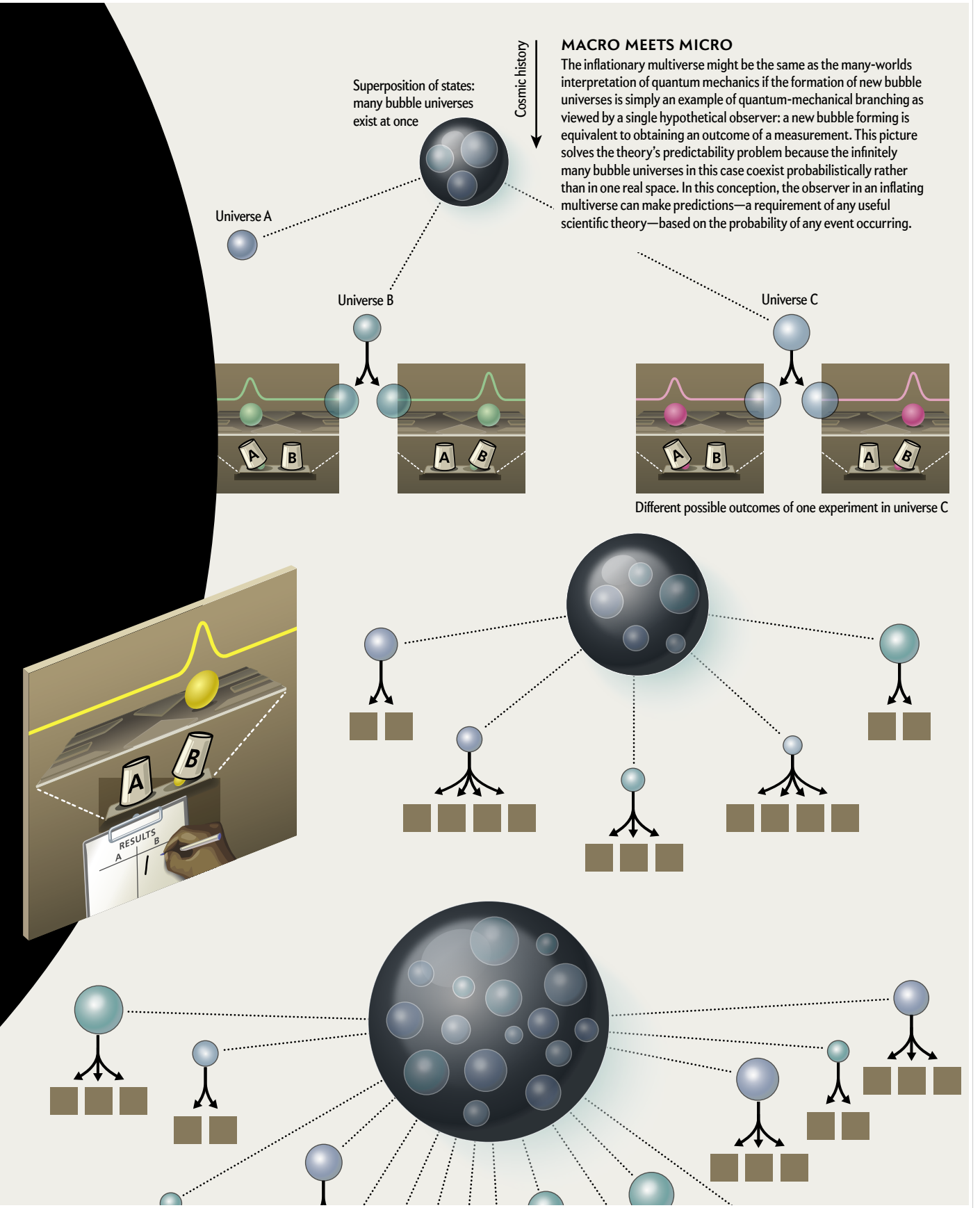

MACRO MEETS MICRO

The inflationary multiverse might be the same as the many-worlds interpretation of quantum mechanics if the formation of new bubble universes is simply an example of quantum-mechanical branching as viewed by a single hypothetical observer: a new bubble forming is equivalent to obtaining an outcome of a measurement. This picture solves the theory's predictability problem because the infinitely many bubble universes in this case coexist probabilistically rather than in one real space. In this conception, the observer in an inflating multiverse can make predictions—a requirement of any useful scientific theory—based on the probability of any event occurring.

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which the observer finds, and keeps finding, that the ball landed at point B. This feature explains why the observer—let us say it is a man—thinks that his measurement changes the state of the system; what actually happens is that when he makes a measurement (interacts with the system), he himself divides into two different people who live in two different parallel worlds corresponding to two separate outcomes, A and B.

According to this picture, humans making measurements have no special significance. The state of the entire world continuously branches into many possible parallel worlds that coexist as a superposition. A human observer, being a part of nature, cannot escape from this cycle—the observer keeps splitting into many observers living in many possible parallel worlds, and all are equally "real." An obvious but important implication of this picture is that everything in nature obeys the laws of quantum mechanics, whether small or large.

I AND OTHER PHYSICISTS ARE ALSO PURSUING THE QUANTUM MULTIVERSE IDEA FURTHER. HOW CAN WE DETERMINE THE QUANTUM STATE OF THE ENTIRE MULTIVERSE? WHAT IS TIME, AND HOW DOES IT EMERGE?

What does this interpretation of quantum mechanics have to do with the multiverse discussed earlier, which seems to exist in a continuous real space rather than as parallel realities? In 2011 I argued that the eternally inflating multiverse and quantum-mechanical many worlds à la Everett are the same concept in a specific sense. In this understanding, the infinitely large space associated with eternal inflation is a kind of "illusion"—the many bubble universes of inflation do not all exist in a single real space but represent the possible different branches on the probabilistic tree. Around the same time that I made this proposal, Raphael Bousso of the University of California, Berkeley, and Leonard Susskind of Stanford University put forth a similar idea. If true, the many-worlds interpretation of the multiverse would mean that the laws of quantum mechanics do not operate solely in the microscopic realm—they also play a crucial role in determining the global structure of the multiverse even at the largest distance scales.

BLACK HOLE QUANDARY

TO BETTER EXPLAIN how the many-worlds interpretation of quantum mechanics could describe the inflationary multiverse, I must digress briefly to talk about black holes. Black holes are extreme warps in spacetime whose powerful gravity prevents objects that fall into them from escaping. As such, they provide an ideal testing ground for physics involving strong quantum and gravitational effects. A particular thought experiment about these entities reveals where the traditional way of thinking about the multiverse goes off track, thereby making prediction impossible.

Suppose we drop a book into a black hole and observe from the outside what happens. Whereas the book itself can never escape the black hole, theory predicts that the information in the book will not be lost. After the book has been shredded by the black hole's gravity and after the black hole itself has gradually evaporated by emitting faint radiation (a phenomenon known as Hawking radiation, discovered by physicist Stephen Hawking of the University of Cambridge), outside observers can reconstruct all the information contained in the initial book by closely examining the radiation released. Even before the black hole has completely evaporated, the book's information starts to slowly leak out via each piece of Hawking radiation.

Yet a puzzling thing occurs if we think about the same situation from the viewpoint of someone who is falling into the black hole along with the book. In this case, the book seems to simply pass through the boundary of the black hole and stay inside. Thus, to this inside observer, the information in the book is also contained within the black hole forever. On the other hand, we have just argued that from a distant observer's point of view, the information will be *outside*. Which is correct? You might think that the information is simply duplicated: one copy inside and the other outside. Such a solution, however, is impossible. In quantum mechanics, the so-called no-cloning theorem prohibits faithful, full copying of information. Therefore, it seems that the two pictures seen by the two observers cannot both be true.

Physicists Gerard 't Hooft of Utrecht University in the Netherlands, Susskind and their collaborators have proposed the following solution: the two pictures can both be valid but not at the same time. If you are a distant observer, then the information is outside. You need not describe the interior of the black hole, because you can never access it even in principle; in fact, to avoid cloning information, you must think of the interior spacetime as nonexistent. On the other hand, if you are an observer falling into the hole, then the interior is all you have, and it contains the book and its information. This view, however, is possible only at the cost of ignoring the Hawking radiation being emitted from the black hole—but such a conceit is allowed because you yourself have crossed the black hole boundary and accordingly are trapped inside, cut off from the radiation emitted from the boundary. There is no inconsistency in either of these two viewpoints; only if you artificially "patch" the two, which you can never physically do, given that you cannot be both a distant and a falling observer at the same time, does the apparent inconsistency of information cloning occur.

COSMOLOGICAL HORIZONS

THIS BLACK HOLE CONUNDRUM may seem unrelated to the issue of how the many-worlds notion of quantum mechanics and the multiverse can be connected, but it turns out that the boundary of a black hole is similar in important ways to the so-called cosmological horizon—the boundary of the spacetime region within which we can receive signals from deep space. The horizon exists because space is expanding exponentially, and objects farther than this cutoff are receding faster than the speed of light, so any message from them can never reach us. The situation, therefore, is akin to a black hole viewed by a distant observer. Also, as in the case of the black hole, quantum mechanics requires an observer inside the horizon to view spacetime on the other side of the boundary—in this case, the exterior of the cosmological horizon—as nonexistent. If we consider such spacetime in addition to the information that can be retrieved from the horizon later (analogous to Hawking radia-

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tion in the black hole case), then we are overcounting the information. This problem implies that any description of the quantum state of the universe should include only the region within (and on) the horizon—in particular, there can be no infinite space in any single, consistent description of the cosmos.

If a quantum state reflects only the region within the horizon, then where is the multiverse, which we thought existed in an eternally inflating infinite space? The answer is that the creation of bubble universes is probabilistic, like any other process in quantum mechanics. Just as a quantum measurement could spawn many different results distinguished by their probability of occurring, inflation could produce many different universes, each with a different probability of coming into being. In other words, the quantum state representing eternally inflating space is a superposition of worlds—or branches—representing different universes, with each of these branches including only the region within its own horizon.

Because each of these universes is finite, we avoid the problem of predictability that was raised by the prospect of an infinitely large space that encompasses all possible outcomes. The multiple universes in this case do not all exist simultaneously in real space—they coexist only in "probability space," that is, as possible outcomes of observations made by people living inside each world. Thus, each universe—each possible outcome—retains a specific probability of coming into being.

This picture unifies the eternally inflating multiverse of cosmology and Everett's many worlds. Cosmic history then unfolds like this: the multiverse starts from some initial state and evolves into a superposition of many bubble universes. As time passes, the states representing each of these bubbles further branch into more superpositions of states representing the various possible outcomes of "experiments" performed within those universes (these need not be scientific experiments—they can be any physical processes). Eventually the state representing the whole multiverse will thus contain an enormous number of branches, each of which represents a possible world that may arise from the initial state. Quantum-mechanical probabilities therefore determine outcomes in cosmology and in microscopic processes. The multiverse and quantum many worlds are really the same thing; they simply refer to the same phenomenon—superposition—occurring at vastly different scales.

In this new picture, our world is only one of all possible worlds that are allowed by the fundamental principles of quantum physics and that exist simultaneously in probability space.

THE REALM BEYOND

TO KNOW IF THIS IDEA is correct, we would want to test it experimentally. But is that feasible? It turns out that discovery of one particular phenomenon would lend support to the new thinking. The multiverse could lead to a small amount of negative spatial curvature in our universe—in other words, objects would travel through space not along straight lines as in a flat cosmos but along curves, even in the absence of gravity. Such curvature could happen because, even though the bubble universes are finite as seen from the perspective of the entire multiverse, observers inside a bubble would perceive their universe to be infinitely large, which would make space seem negatively curved (an example of negative curvature is the surface of a saddle, whereas the surface of a sphere is positively curved). If we were inside one such bubble, space should likewise appear to us to be bent.

Evidence so far indicates that the cosmos is flat, but experiments studying how distant light bends as it travels through the cosmos are likely to improve measures of the curvature of our universe by about two orders of magnitude in the next few decades. If these experiments find any amount of negative curvature, they will support the multiverse concept because, although such curvature is technically possible in a single universe, it is implausible there. Specifically, a discovery supports the quantum multiverse picture described here because it can naturally lead to curvature large enough to be detected, whereas the traditional inflationary picture of the multiverse tends to produce negative curvature many orders of magnitude smaller than we can hope to measure.

Interestingly, the discovery of positive curvature would falsify the multiverse notion presented here because inflation theory suggests that bubble universes could produce only negative curvature. On the other hand, if we are lucky, we may even see dramatic signs of a multiverse—such as a remnant from a "collision" of bubble universes in the sky, which may be formed in a single branch in the quantum multiverse. Scientists are, however, far from certain if we will ever detect such signals.

I and other physicists are also pursuing the quantum multiverse idea further on a theoretical level. We can ask fundamental questions such as: How can we determine the quantum state of the entire multiverse? What is time, and how does it emerge? The quantum multiverse picture does not immediately answer these questions, but it does provide a framework to address them. Lately, for instance, I have found that constraints imposed by the mathematical requirement that our theory must include rigorously defined probabilities may enable us to determine the unique quantum state of the entire multiverse. These constraints also suggest that the overall quantum state stays constant even though a physical observer, who is a part of the multiverse state, will see that new bubbles constantly form. This implies that our sense of the universe changing over time and, indeed, the concept of time itself may be an illusion. Time, according to this notion, is an "emergent concept" that arises from a more fundamental reality and seems to exist only within local branches of the multiverse.

Many of the ideas I have discussed are still quite speculative, but it is thrilling that physicists can talk about such big and deep questions based on theoretical progress. Who knows where these explorations will finally lead us? It seems clear, though, that we live in an exciting era in which our scientific explorations reach beyond what we thought to be the entire physical world—our universe—into a potentially limitless realm. SA

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MORE TO EXPLORE

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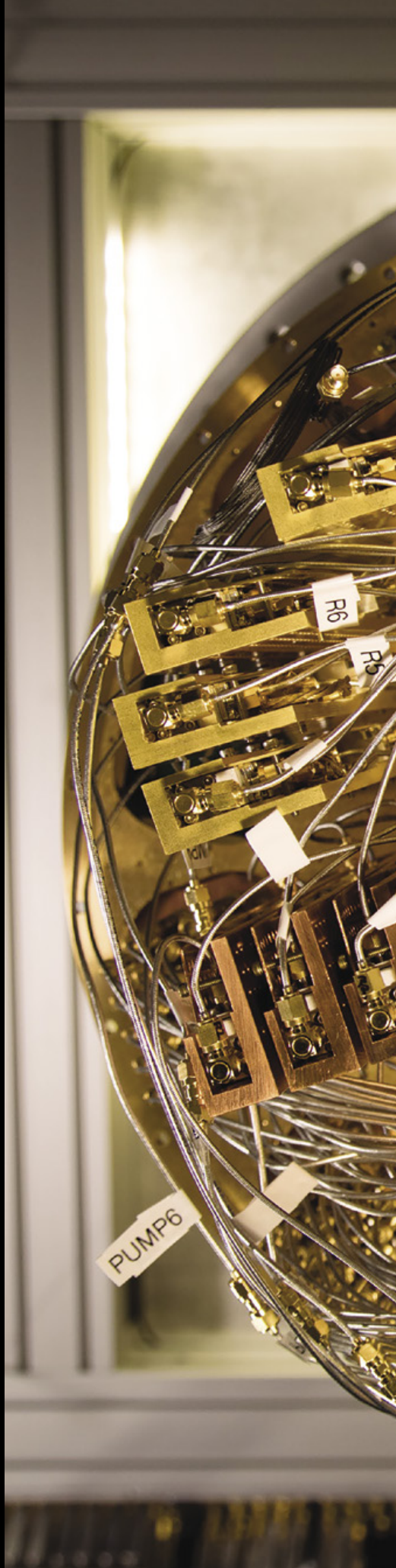
BEFORE THE QUANTUM REVOLUTION

With decades still to go until the first general-purpose quantum computers, the race is on to make today's systems useful

By Michael Brooks



CRYOSTAT used to cool Google quantum-computing hardware.

ERIK LUCERO

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OCCASIONALLY ALÁN ASPURU-GUZIK HAS A MOVIE-STAR moment, when fans half his age will stop him in the street. "They say, 'Hey, we know who you are,'" he laughs. "Then they tell me that they also have a quantum start-up and would love to talk to me about it." He doesn't mind a bit. "I don't usually have time to talk, but I'm always happy to give them some tips." That affable approach is not uncommon in the quantum-computing community, says Aspuru-Guzik, who is a computer scientist at the University of Toronto and co-founder of Zapata Computing in Cambridge, Mass. Although grand claims have been made about a looming revolution in computing, and private investment has been flowing into quantum technology, it is still early days, and no one is sure whether it is even possible to build a useful quantum computer.

IN BRIEF

General-purpose quantum computers are decades away, despite recent demonstrations of so-called quantum supremacy. **In the meantime** intermediate quantum systems are offering valuable, immediate insights into multiple fields, such as chemistry, machine learning, materials science and cryptography. **In fields such as** machine learning, researchers are building on both quantum and classical algorithms, accelerating the speed of both. **Some see** this short-term quantum computing as a type of controlled experimental environment, which promises to drive discovery in the field.

Today's quantum machines have at best a few dozen quantum bits, or qubits, and they are often beset by computation-destroying noise. Researchers are still decades—and many thousands of qubits—away from general-purpose quantum computers, ones that could do long-heralded calculations such as factoring large numbers. A team at Google has now reportedly demonstrated a quantum computer that can outperform conventional machines, but such "quantum supremacy" is expected to be extremely limited. For general applications, 30 years is "not an unrealistic timescale," says physicist John Preskill of the California Institute of Technology. Some researchers have raised the possibility that, if quantum computers fail to deliver anything of use soon, a quantum winter will descend: enthusiasm will wane and funding will dry up before researchers get anywhere close to building full-scale machines. "Quantum winter is a real concern," Preskill says. Yet he remains upbeat because the slow progress has forced researchers to adjust their focus and see whether the devices they have already built might be able to do something interesting in the near future.

Judging from a flurry of papers published during the past few years, it's a definite possibility. This is the era of the small, error-prone, or "noisy intermediate-scale quantum" (NISQ), machine, as Preskill has put it. And so far it has turned out to be a much more interesting time than anyone had anticipated. Although the results are still quite preliminary, algorithm designers are finding work for NISQ machines that could have an immediate impact in chemistry, machine learning, materials science and cryptography—offering insights into the creation of chemical catalysts, for example. These innovations are also provoking unexpected progress in conventional computing. All this activity is running alongside efforts to build bigger, more robust quantum systems. Aspuru-Guzik advises people to expect the unexpected. "We're here for the long run," he says. "But there might be some surprises tomorrow."

FRESH PROSPECTS

QUANTUM COMPUTING might feel like a 21st-century idea, but it came to life the same year that IBM released its first personal computer. In a 1981 lecture, physicist Richard Feynman pointed out that the best way to simulate real-world phenomena that have a quantum-mechanical basis, such as chemical reactions or the properties of semiconductors, is with a machine that follows quantum-mechanical rules. Such a computer would make use of entanglement, a

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RESEARCHERS at Zapata Computing, including co-founder Alán Asparu-Guzik (*fourth from left*), are building quantum algorithms for today's systems.

DOUG LEVY

phenomenon unique to quantum systems. With entanglement, a particle's properties are affected by what happens to other particles with which it shares intimate quantum connections. These links give chemistry and many branches of materials science a complexity that defies simulation on classical computers. Algorithms designed to run on quantum computers aim to make a virtue of these correlations, performing computational tasks that are impossible on conventional machines.

Yet the same property that gives quantum computers such promise also makes them difficult to operate. Noise in the environment, whether from temperature fluctuations, mechanical vibrations or stray electromagnetic fields, weakens the correlations among qubits, the computational units that encode and process information in the computer. That degrades the reliability of the machines, limits their size and compromises the kinds of computation that they can perform. One potential way to address the issue is to run error-correction routines. Such algorithms, however, require their own qubits—the theoretical minimum is five error-correcting qubits for every qubit devoted to computation—adding a lot of overhead costs and further limiting the size of quantum systems.

Some researchers are focusing on hardware. Microsoft Quantum's multinational team is attempting to use exotic "topological particles" in extremely thin semiconductors to construct qubits that are much more robust than today's quantum systems. But these workarounds are longer-term projects, and many researchers are focusing on what can be done with the noisy small-scale machines that are available now—or will be in the next five to 10 years. Instead of aiming for a universal, error-corrected quantum computer, for example, physicist Pan Jian-Wei and his team at the University of Science and Technology of China in Hefei are pursuing short- and mid-term targets. That includes quantum supremacy and developing quantum-based simulators that can solve meaningful problems in areas such as materials science. "I usually refer to it as 'laying eggs along the way,'" he says.

Bert de Jong of Lawrence Berkeley National Laboratory has his eye on applications in chemistry, such as finding alternatives to the Haber process for the manufacture of ammonia. At the moment, researchers must make approximations to run their simulations on classical machines, but that approach has its limits. "To enable large scientific advances in battery research or any scientific area rely-

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ing on strong electron correlation," he says, "we cannot use the approximate methods." NISQ systems won't be able to perform full-scale chemistry simulations. But when combined with conventional computers, they might demonstrate an advantage over existing classical simulations. "The classically hard part of the simulation is solved on a quantum processor, while the rest of the work is done on a classical computer," de Jong says.

This kind of hybrid approach is where Aspuru-Guzik earned his fame. In 2014 he and his colleagues devised an algorithm called the variational quantum eigensolver (VQE), which uses conventional machines to optimize guesses. Those guesses might be about the shortest path for a traveling salesperson, the best shape for an aircraft wing or the arrangement of atoms that constitutes the lowest energy state of a particular molecule. Once that best guess has been identified, the quantum machine searches through the nearby options. Its results are fed back to the classical machine, and the process continues until the optimum solution is found. As one of the first ways to use NISQ machines, VQE had an immediate impact, and teams have used it on several quantum computers to find molecular ground states and explore the magnetic properties of materials.

"THE CLASSICALLY HARD PART OF THE SIMULATION IS SOLVED ON A QUANTUM PROCESSOR, WHILE THE REST OF THE WORK IS DONE ON A CLASSICAL COMPUTER."

—BERT DE JONG
Lawrence Berkeley National Lab

That same year Edward Farhi, then at the Massachusetts Institute of Technology, proposed another heuristic, or best-guess, approach called the quantum approximation optimization algorithm (QAOA). The QAOA, another quantum-classical hybrid, performs what is effectively a game of quantum educated guessing. The only application so far has been fairly obscure—optimizing a process for dividing up graphs—but the approach has already generated some promising spin-offs, says Eric Anschuetz, a graduate student at M.I.T., who has worked at Zapata. One of those, devised by Anschuetz and his colleagues, is an algorithm called variational quantum factoring (VQF), which aims to bring the encryption-breaking, large-number-factoring capabilities of quantum processing to NISQ-era machines.

Until VQF, the only known quantum algorithm for such work was one called Shor's algorithm. That approach offers a fast route to factoring large numbers but is likely to require hundreds of thousands of qubits to go beyond what is possible on classical machines. In a paper published in 2019, Zapata researchers suggest that VQF might be able to outperform Shor's algorithm on smaller systems within a decade. Even so, no one expects VQF to beat a classical machine in that time frame. Others are looking for more general ways to make the most of NISQ hardware. Instead of diverting qubits to correct noise-induced errors, for example, some scientists have devised a way to work with the noise. With "error mitigation," the same routine is run on a noisy processor multiple times. By comparing the results of runs of different lengths, researchers can learn the systematic effect of noise on the computation and estimate what the result would be without noise.

The approach looks particularly promising for chemistry. In March 2019 a team led by physicist Jay Gambetta of IBM's Thomas J. Watson Research Center in Yorktown Heights, N.Y., showed that error mitigation can improve chemistry computations performed on a four-qubit computer. The team used the approach to calculate basic properties of the molecules hydrogen and lithium hydride, such as how their energy states vary with interatomic distance. Although single, noisy runs did not map onto the known solution, the error-mitigated result matched it almost exactly.

Errors might not even be a problem for some applications. Vedran Dunjko, a computer scientist and physicist at the University of Leiden in the Netherlands, notes that the kinds of tasks performed in machine learning, such as labeling images, can cope with noise and approximations. "If you're classifying an image to say whether it is a human face, or a cat or a dog, there is no clean mathematical description of what these things look like—and nor do we look for one," he says.

FUZZY FUTURE

GAMBETTA'S TEAM at IBM has also been pursuing quantum machine learning for NISQ systems. In early 2019, while working with researchers at the University of Oxford and at M.I.T., the group reported two quantum machine-learning algorithms that are designed to pick out features in large data sets. It is thought that as quantum systems get bigger, their data-handling capabilities should grow exponentially, ultimately allowing them to handle many more data points than classical systems can. The algorithms provide "a possible path to quantum advantage," the team wrote.

But as with other examples in the machine-learning field, no one has yet managed to demonstrate a quantum advantage. In the era of NISQ computing, there is always a "but." Zapata's factoring algorithm, for instance, might never factor numbers faster than classical machines. No experiments have been done on real hardware yet, and there is no way to definitively, mathematically prove superiority.

Other doubts are arising. Gian Giacomo Guerres-

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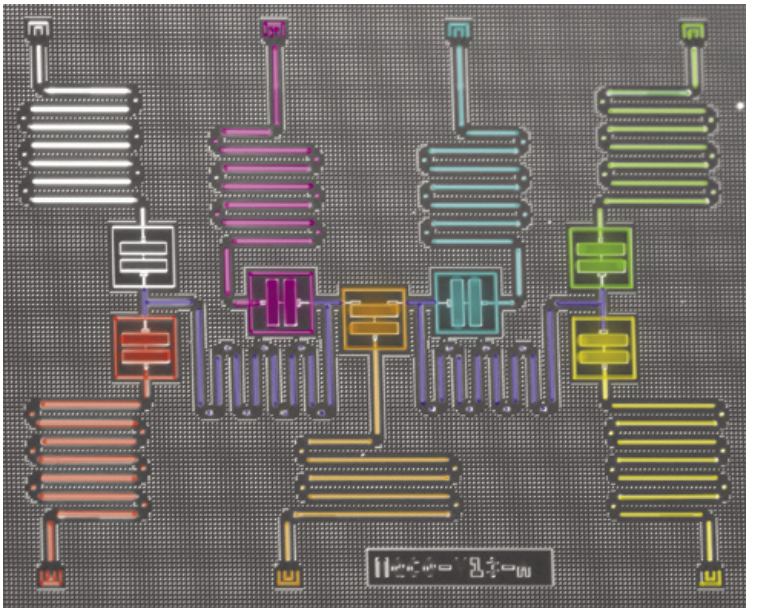
chi and Anne Matsuura of Intel Labs in Santa Clara, Calif., performed simulations of Farhi's QAOA algorithms and found that real-world problems with realistically modeled noise do not fare well on machines the size of today's NISQ systems. "Our work adds a word of caution," Guerreschi says. "If order-of-magnitude improvements to the QAOA protocols are not introduced, it will take many hundreds of qubits to outperform what can be done on classical machines." One general problem for NISQ computing, Dunjko points out, comes down to time.

Conventional computers can effectively operate indefinitely. A quantum system can lose its correlations, and thus its computing power, in fractions of a second. As a result, a classical computer does not have to run for very long before it can outstrip the capabilities of today's quantum machines. NISQ research has also created a challenge for itself by focusing attention on the shortcomings of classical algorithms. It turns out that many of those, when investigated, can be improved to the point at which quantum algorithms cannot compete.

In 2016, for instance, researchers developed a quantum algorithm that could draw inferences from large data sets. It is known as a type of recommendation algorithm because of its similarity to the "you might also like" algorithms used online. Theoretical analysis suggested that this scheme was exponentially faster than any known classical algorithm. But last July computer scientist Ewin Tang, then an undergraduate student at the University of Texas at Austin, formulated a classical algorithm that worked even faster. Tang has since generalized her tactic, taking processes that make quantum algorithms fast and reconfiguring them so that they work on classical computers. This has allowed her to strip the advantage from a few other quantum algorithms, too.

Despite the thrust and parry, researchers say it is a friendly field and one that is improving both classical computing and quantum approaches. "My results have been met with a lot of enthusiasm," says Tang, who is now a Ph.D. student at the University of Washington. For now, however, researchers must contend with the fact that there is still no proof that today's quantum machines will yield anything of use. NISQ could simply turn out to be the name for the broad, possibly featureless landscape researchers must traverse before they can build quantum computers capable of outclassing conventional ones in helpful ways.

"Although there were a lot of ideas about what we could do with these near-term devices," Preskill says, "nobody really knows what they are going to be good for." De Jong, for one, is okay with the uncertainty. He sees the short-term quantum processor as more of a lab bench—a controlled experimental environment. The noise component of NISQ might even be seen as a benefit because real-world systems, such as potential molecules for use in solar cells, are also affected by their surroundings. "Exploring how a quantum system responds to its environment is crucial to obtain the understanding needed to drive new scientific discovery," he says.



FALSE-COLOR image of a seven-qubit system that has been used for quantum chemistry computations.

For his part, Aspuru-Guzik is confident that something significant will happen soon. As a teenager in Mexico, he used to hack phone systems to get free international calls. He says he sees the same adventurous spirit in some of the young quantum researchers he meets—especially now that they can effectively "dial in" and try things out on the small-scale quantum computers and simulators made available by companies such as Google and IBM. This ease of access, he thinks, will be key to working out the practicalities.

"You have to hack the quantum computer," Aspuru-Guzik says. "There is a role for formalism, but there is also a role for imagination, intuition and adventure. Maybe it's not about how many qubits we have; maybe it's about how many hackers we have." SA

Michael Brooks is a freelance writer based in Lewes, England.

MORE TO EXPLORE

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The Quantum Internet Is Emerging—

One Experiment at a Time

Breakthrough demonstrations using defective diamonds, high-flying drones, laser-bathed crystals and other exotica suggest practical, unhackable quantum networks are within reach

By Anil Ananthaswamy

TODAY'S INTERNET IS A PLAYGROUND FOR HACKERS. FROM INSECURE COMMUNICATION links to inadequately guarded data in the cloud, vulnerabilities are everywhere. But if quantum physicists have their way, such weaknesses will soon go the way of the dodo. They want to build quantum networks sporting full-blown quantumness, where information is created, stored and moved around in ways that mirror the bizarre behavior of the quantum world—think of the metaphorical cats that can be both dead and alive or particles that can exert "spooky action at a distance." Freed from many limitations of "classical" networks, these systems could provide a level of privacy, security and computational clout that is impossible to achieve with today's Internet.

Although a fully realized quantum network is still a far-off vision, recent breakthroughs in transmitting, storing and manipulating quantum information have convinced some physicists that a simple proof of principle is imminent.

From defects in diamonds and crystals that help photons change color, to drones that serve as spooky network nodes, researchers are using a smorgasbord of exotic materials and techniques in this quantum quest. The first stage, many say, would be a quantum network using standard optical fiber to connect at least three small quantum devices about 50 to 100 kilometers apart.

Such a network may be built in the next five years, according to Ben Lanyon of the Institute for Quantum Optics and Quantum Information in Innsbruck, Austria. Lanyon's team is part of Europe's Quantum Internet Alliance, coordinated by Stephanie Wehner of the Delft University of Technology in the Netherlands, which is tasked with creating a quantum network. Europe is competing with similar national efforts in China—which in

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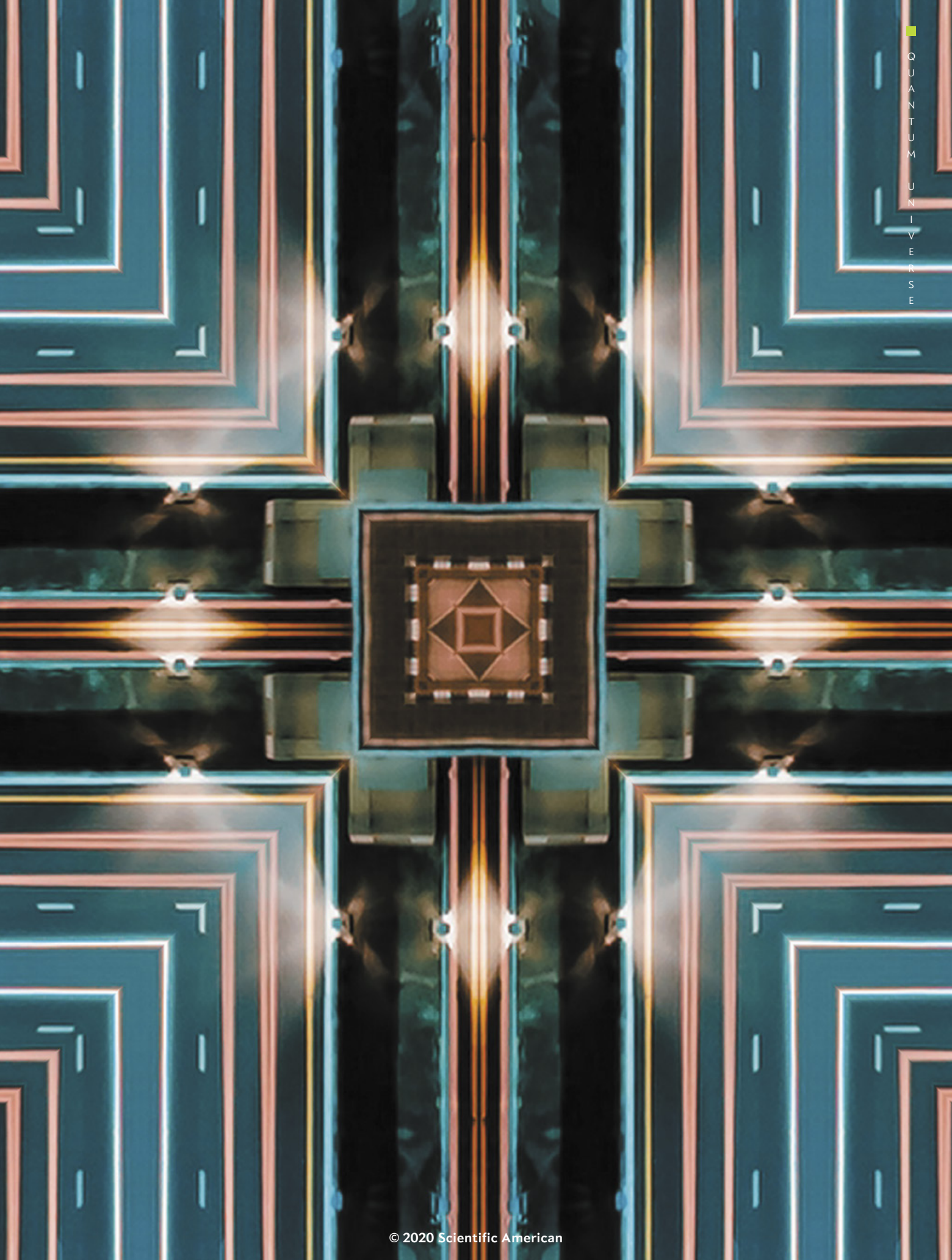

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2016 launched Micius, a quantum communications satellite—as well as in the U.S. Last December the U.S. government enacted the National Quantum Initiative Act, which will lavishly fund a number of research hubs dedicated to quantum technologies, including quantum computers and networks. "The main feature of a quantum network is that you are sending quantum information instead of classical information," says Delft University's Ronald Hanson. Classical information deals in bits that have values of either 0 or 1. Quantum information, however, uses quantum bits, or qubits, which can be in a superposition of both 0 and 1 at the same time. Qubits can be encoded, for example, in the polarization states of a photon or in the spin states of electrons and atomic nuclei.

QUANTUM NETWORKING

IN WHAT HANSON CALLS the "low hanging fruit of quantum networks," qubits are already being used for creating secret keys—random strings of 0s and 1s—that can then be used to encode classical information, an application called quantum key distribution (QKD).

QKD involves one party, say Alice, sending qubits to Bob, who measures the qubits (Alice and Bob first appeared in a 1978 paper on public key cryptography, and have now become placeholders for nodes in a quantum network). Only for certain types of measurements will Bob get the same value that Alice encoded in the qubits. Alice and Bob can compare notes over a public channel to figure out what those measurements are, without actually sharing the qubit values. They can then use those private values to create a secret shared key to encrypt classical messages. Crucially, if an intruder were to intercept the qubits, Alice and Bob could detect the intrusion, discard the qubits and start over—theoretically continuing until no one is eavesdropping on the quantum channel.

In July 2018 Alberto Boaron of the University of Geneva and his colleagues reported distributing secret keys using QKD over a record distance of more than 400 kilometers of optical fiber, at 6.5 kilobits per second. In contrast, commercially available systems, such as the one sold by the Geneva-based company ID Quantique, provide QKD over 50 kilometers of fiber.

ALICE AND BOB GET SPOOKY

IDEALLY quantum networks will do more than QKD. The next step would be to transfer quantum states directly between nodes. Whereas qubits encoded using a photon's polarization can be sent over optical fibers (as is done with QKD), using such qubits to transfer large amounts of quantum information is problematic. Photons can get scattered or absorbed along the way or may simply fail to register in a detector, making for an unreliable transmission channel. Fortunately, there is a more robust way to exchange quantum information—via the use of another property of quantum systems, called entanglement.

When two particles or quantum systems interact, they can get entangled. Once entangled, both systems are described by a single quantum state, so measuring the state of one system instantly influences the state of the other, even if they are kilometers apart. Albert Einstein called entanglement "spooky action at a distance," and it is an invaluable resource for quantum networks. Imagine two network nodes, Alice and Bob, each made of some isolated bit of matter (the most obvious and reliable substrate for encoding and storing quantum states). Such "matter nodes" can become entangled with each other via a process that involves the exchange of entangled photons.

Using entangled matter nodes, Alice can exploit her share of the entanglement to send an entire qubit to Bob, without actually transmitting a physical qubit, making the transfer foolproof and secure. The key here is that once entanglement is established between the nodes, the protocol to transfer qubits from Alice to Bob is robust and deterministic.

But to do this across long distances, one first needs to distribute the entanglement—usually via standard fiber-optic networks. In January 2019, Lanyon's team in Innsbruck reported setting the record for creating entanglement between matter and light over 50 kilometers of optical fiber.

For matter, Lanyon's team used a so-called trapped ion—a single calcium ion confined to an optical cavity using electromagnetic fields. When manipulated with lasers, the ion ends up encoding a qubit as a superposition of two energy states, while also emitting a photon, with a qubit encoded in its polarization states. The qubits in the ion and the photon are entangled. The task: to send this photon through an optical fiber while preserving the entanglement.

Unfortunately, the trapped ion emits a photon at a wavelength of 854 nanometers (nm), which does not last long inside an optical fiber. Thus, Lanyon's team sent the emitted photon into something called a nonlinear crystal being pumped with a powerful laser. The entire interaction converts the incoming photon into another of "telecom" wavelength, one well suited for optical fibers.

The Innsbruck team then injected this photon into a 50-kilometer-long section of optical fiber. Once it reached the other end, they tested the ion and the photon to see if they were still entangled. They were.

SWAPPING ENTANGLEMENTS

LANYON'S TEAM now wants to entangle two trapped ion nodes that are 100 kilometers apart. Each node would transmit an entangled photon through 50 kilometers of optical fiber to a station in the middle. There the photons would be measured in such a way that they lose entanglement with their respective ions, causing the ions themselves to get entangled with each other. As a consequence, the two nodes, 100 kilometers apart, will each form a quantum link via a pair of entangled qubits. The entire process is called entanglement swapping. Though relatively inefficient for now, Lanyon calls the setup "a good start" for developing better, faster swapping systems.

Meanwhile Hanson's team at Delft has demonstrated how to entangle a different type of matter node with a telecom-wavelength photon. The researchers used a defect in diamond called a nitrogen-vacancy (NV) center. The defect arises when a nitrogen atom replaces a carbon atom in the gem's crystalline structure, leaving a vacancy in the crystal lattice adjacent to the nitrogen atom. The team used lasers to manipulate the spin of one "free" electron in the diamond NV center, placing the electron in a superposition of spin states, thus encoding one qubit. The process also results in the emission of a photon. The photon is in a superposition of being emitted in one of two consecutive time slots. "The photon is always there, but in a superposition of being emitted early or late," Hanson says. The qubit stored in the electron's spin and the qubit stored in the photon's presence or absence in the time slots are now entangled.

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In 2015 the Delft team placed two spatially separated matter nodes made of diamond NV centers about 1.3 kilometers apart, linked by optical fiber. The group then transmitted an entangled photon from each node to a point roughly midway on the path between these two nodes. There the team swapped the entanglement, causing the two NV centers to become entangled. But just as with Lanyon's experiment, the photons emitted by the Delft team's apparatus have a wavelength of 637 nm. Such photons are terrible travelers when injected into optical fibers, diminishing in intensity by an order of magnitude for every kilometer they travel. "It makes it impossible to go beyond a few kilometers," Hanson says.

So, in May 2019, the Delft team reported a remedy similar to that developed by the Innsbruck team, also using nonlinear crystals and lasers to convert the photon to telecom wavelengths. In this approach, the qubits encoded by the NV center and telecom-wavelength photon remained entangled, setting the stage for entanglement swapping between two diamond NV center nodes.

Although they have not yet transmitted a diamond-entangled telecom-wavelength photon via any significant length of optical fiber, Hanson is confident that they can do so and then entangle diamond NV centers 30 kilometers apart using entanglement swapping. "We are now building two of these nodes," he says. "We'll use glass fiber that's already in the ground to entangle these two NV centers." The team's next goal is to entangle nodes using the preexisting fiber infrastructure between three cities in the Netherlands, where distances are amenable to such state-of-the-art experiments.

THESE QUANTUM SYSTEMS COULD PROVIDE A LEVEL OF PRIVACY, SECURITY AND COMPUTATIONAL CLOUT THAT IS IMPOSSIBLE TO ACHIEVE WITH TODAY'S "CLASSICAL" INTERNET.

MIX AND MATCH: THE CHALLENGE AHEAD

THE INNSBRUCK AND DELFT TEAMS each worked with only one type of matter for storing and entangling qubits. But real-life quantum networks may use different types of materials in each node, depending on the exact task at hand—for example, quantum computation or quantum sensing. And quantum nodes, besides manipulating qubits, may also have to store them for brief periods, in so-called quantum memories.

"It's still not clear what's going to be the right platform and the right protocol," says Marcelli Grimau Puigibert of the University of Basel in Switzerland. "It's always good to be able to connect different hybrid systems."

To this end, Puigibert, working with Wolfgang Tittel's team at the University of Calgary, recently showed how to entangle qubits stored in two different types of materials. They started with a source that emits a pair of entangled photons, one at a wavelength of 794 nm and the other at 1,535 nm. The 794-nm photon interacts with a lithium-niobate crystal doped with thulium, so that the photon's state becomes stored in the crystal. The 1,535-nm photon goes into an erbium-doped fiber, which also stores the quantum state.

Both memories were designed to reemit photons at a particular time. The team analyzed those reemitted photons and showed that they remained entangled. This, in turn, implies that the quantum memories were also entangled just prior to emitting those photons, thus preserving entanglement over time.

The photon wavelengths were also designed to cross-connect different transmission systems: optical fibers on one end (1,535 nm) and satellite communications on the other (794 nm). The latter is important because if quantum networks are to go intercontinental, entanglement will need to be distributed via satellites. In 2017 a team led by Jian-Wei Pan of the University of Science and Technology of China in Hefei used Micius, China's quantum satellite, to distribute entanglement between ground stations on the Tibetan Plateau and southwest China.

Satellites, however, seem destined to remain an expensive, niche option of last resort for quantum networks. The next best choice may be relatively inexpensive drones. In May 2019, Shi-Ning Zhu of Nanjing University and his colleagues reported that they had used a 35-kilogram drone to send entangled photons to two quantum nodes 200 meters apart on the ground. The experiment used a classical communication link between the nodes to confirm that the photons they received were indeed entangled. The experiment succeeded in significantly varying conditions, working in sunlight and in darkness and even on rainy nights. If such drones can be scaled up and installed on high-altitude unmanned aerial vehicles, the distance between the nodes on the ground can extend to about 300 kilometers, the authors write.

Challenges remain in the march toward a fully functioning quantum network. Reliable quantum memories are one. Another important missing piece is the ability to extend the reach of a quantum link to arbitrarily long distances, using so-called quantum repeaters. Quantum states cannot be simply copied and regurgitated, as is done with classical information. Quantum nodes will need sophisticated quantum logic gates to ensure that entanglement is preserved in face of losses from interaction with the environment. "It's definitely one of the next big challenges," Lanyon says.

Nevertheless, the basic elements are falling into place for building a quantum network that connects at least three cities—and, perhaps, eventually the world. "We now have platforms with which we can start to explore true quantum networks for the first time," Hanson says. More sophisticated networks beckon. "There's no guarantee. There's only promise there [of] the cool stuff we'll be able to do if we succeed." SA

Anil Ananthaswamy is author of *The Edge of Physics, The Man Who Wasn't There* and, most recently, *Through Two Doors at Once: The Elegant Experiment That Captures the Enigma of Our Quantum Reality.*

MORE TO EXPLORE

Entanglement Between a Diamond Spin Qubit and a Photonic Time-Bin Qubit at Telecom Wavelength. Anna Tchebotareva et al. in *Physical Reviews Letters,* Vol. 123, Article 063601; August 5, 2019.

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An update to a classic experiment establishes new quantum-mechanical truths and paves the way toward a novel strategy for quantum computing

THE TRIPLE-SLIT EXPERIMENT

By Urbasi Sinha

Illustration by Andrea Ucini

"ALL OF THE MYSTERY OF QUANTUM MECHANICS" is contained within the double-slit experiment, Nobel laureate Richard Feynman famously said. In the experiment, first proposed in 1801 by British polymath Thomas Young, a beam of photons—particles of light—flies toward a wall with two slits

IN BRIEF

The "double-slit" experiment revealed that light and matter are both particles and waves and demonstrated the superposition principle: that particles can be in multiple states and locations simultaneously.

Recently scientists have run versions of the experiment with three slits instead of two. The change has revealed new details about how the superposition must be calculated in slit-experiment boundary conditions.

The triple-slit experiment is also helpful in quantum computing. It offers the chance to create three-dimensional quantum bits (instead of the usual two), which may help scale up quantum computers to useful size.

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cut in it. When the light reaches a screen behind the wall, it produces a telltale "interference pattern": stripes of light interspersed with darkness. This pattern results only if the photons act like waves rather than like point particles, and the peaks and troughs of the waves coming through the two slits interfere with one another, sometimes adding light and sometimes canceling it out. When Young performed the experiment, using a modified setup, it seemed to establish that light was a wave and not a particle.

Or was it? Weirdly, in experiments centuries later in which researchers took care to shine only one photon at a time toward the wall, the interference pattern remained, as if a single particle were interfering with itself. Even stranger, if you place a detector by the slits to record which slit each particle passes through, the interference pattern disappears. Instead you get two lines of light on the screen, just what you would expect if point particles and not waves were passing through—as if the act of measurement changed the nature of the particles.

To this day, the double-slit experiment, with its inherent simplicity of concept, remains one of the most intriguing tests ever performed. It has been repeated many times, with particles of both light and matter. It clearly demonstrates the fundamental strangeness of quantum mechanics: that light, and matter as well, is in fact both a particle and a wave—a concept known as wave-particle duality. It also establishes the superposition principle: particles can exist in multiple states and even simultaneously in multiple places. In the double-slit experiment, particles must not be traveling through one slit or the other—for interference to occur, each particle must be traveling through *both*.

As celebrated as this experiment is, we have not yet plumbed its depths. Recently my team at the Quantum Information and Computing laboratory at the Raman Research Institute in Bangalore, India, has set up "triple-slit" experiments in the microwave-wavelength range—instead of two slits, we use three. It is a seemingly simple adjustment, but it has profound consequences. On the theory side, our triple-slit trials have clarified how the superposition principle applies in these circumstances and have revealed new subtleties in our fundamental understanding of this phenomenon.

Our triple-slit experiment architecture also offers intriguing opportunities in the emerging field of quantum computing. Quantum computers promise to enable calculations that were previously intractable—if we can harness the power of quantum physics to build them. One of the central challenges in quantum computing is finding a way to increase the number of bits a quantum computer contains, called qubits, without destroying the superposition that allows qubits to be in two states at once—the key to achieving huge gains in computing speed. Whereas most of the community is working on increasing the number of qubits in a system, my lab is trying an alternative, less explored approach by using higher-dimensional "qudits" instead of two-dimensional qubits. Using the triple-slit system, we can create three-dimensional qudits called qutrits.

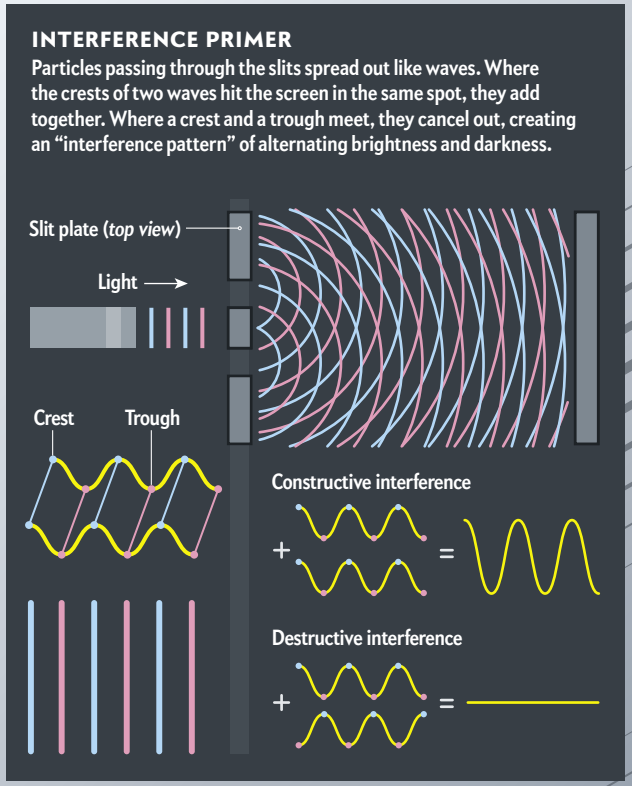
THE SUPERPOSITION PRINCIPLE

QUANTUM THEORY describes fundamental particles not just as physical waves but also as being determined by the so-called wave equation, whose solutions may be designated by the Greek letter psi, ψ. These solutions express the probability amplitude of the particle being in any particular state.

Our research, however, has revealed a flaw in the way physicists have traditionally dealt with wave-equation calculations when they are applied to the double-slit experiment. Imagine the classic experiment and let the two slits be named A and B, respectively. The solutions to the wave equation describing a particle in this system can be labeled ψ_A when slit A is open and ψ_B when slit B is open. What happens when both slits are open? It is common practice in textbooks to call the solution $\psi_A + \psi_B$ to represent the fact that the particle is in a superposition state in which it is passing through both slits. This is indeed an application of the superposition principle, though an incomplete one. The reason is simple: The situation with two slits open at once is not the same as the combination of having the slits open separately. We know that when they are open at the same time, a particle in some ways passes through both and interacts with

Slit Experiments

The famous double-slit experiment established two of the bedrock principles of quantum theory: wave-particle duality—the concept that matter and light are both particles and waves—and superposition, the notion that particles can be in multiple states and locations simultaneously. More recently, scientists have performed versions of the experiment with three slits rather than two, opening the door to new theoretical and technological possibilities.


INTERFERENCE PRIMER
Particles passing through the slits spread out like waves. Where the crests of two waves hit the screen in the same spot, they add together. Where a crest and a trough meet, they cancel out, creating an "interference pattern" of alternating brightness and darkness.
Slit plate (top view)
Light
Crest
Trough
Constructive interference
Destructive interference

Illustrations by Nick Bockelman

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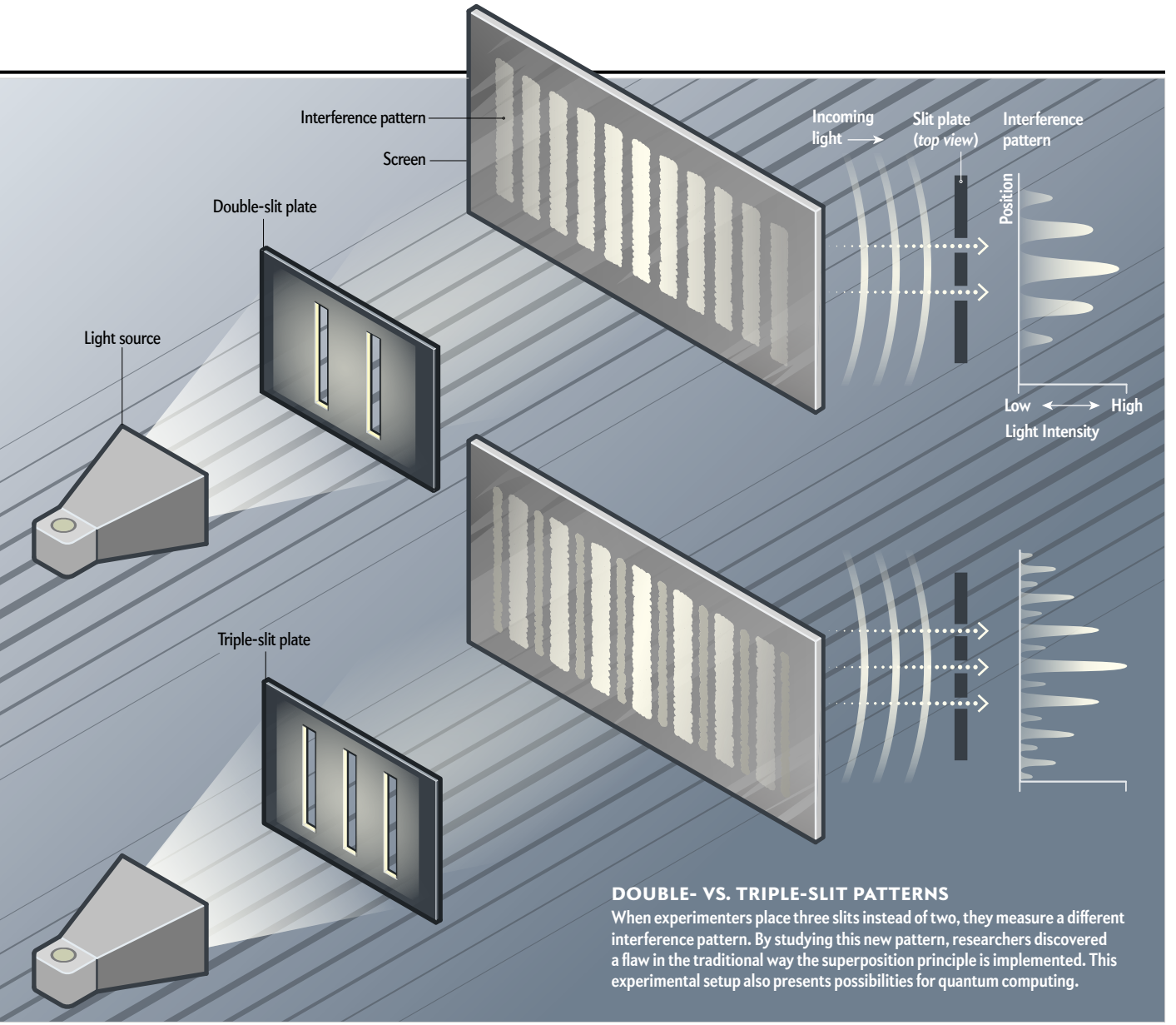

DOUBLE- VS. TRIPLE-SLIT PATTERNS
When experimenters place three slits instead of two, they measure a different interference pattern. By studying this new pattern, researchers discovered a flaw in the traditional way the superposition principle is implemented. This experimental setup also presents possibilities for quantum computing.

itself, and we cannot represent these interactions by simply adding the two solutions.

Scientists have suggested before that some correction term might be needed to make our equations accurate. This quantity is called the Sorkin parameter because it was predicted in 1994 by physicist Rafael Sorkin, then at Syracuse University. Most researchers, however, have assumed that this term would be so small as to be negligible. And indeed, we know it cannot be too large, or it would have been observed much earlier. But our triple-slit experiment proved that this term does exist and that it is not always small enough to be ignored. The use of three or more slits provides us with a natural test bed for this correction term because we can measure a quantity (the Sorkin parameter) that will be zero if the correction term does not exist and nonzero if it does exist. (In the two-slit case, the correction term gets added to something that is already nonzero, so it does not show up in a noticeable way.)

I have been working on triple-slit experiments for more than a decade. In 2010 my colleagues and I published our first results in a paper in *Science*. In 2014 my team and I began to run new trials of our triple-slit experiment using microwaves at the Gauribidanur astronomical observatory in Karnataka, India. We carried out the project in an open field in a tent next to corn crops. Although the setting might sound odd for a precision physics experiment, the corn provided a good source of absorption for stray microwaves that might have interfered with our measurements. It also helped that we were not working with walls or lots of equipment in the space that could reflect waves. Furthermore, our isolated location had poor cell service—another benefit in avoiding contamination—and we were able to run our experiment on a very large scale.

Our setup used two horn antennas—one to release microwave photons and one to detect them. Between them was a plate with three slots, each 10 centimeters wide, spaced 13 centimeters apart. Staying true to the style of the first slit-based experiments, we housed the detector on a rail that we could

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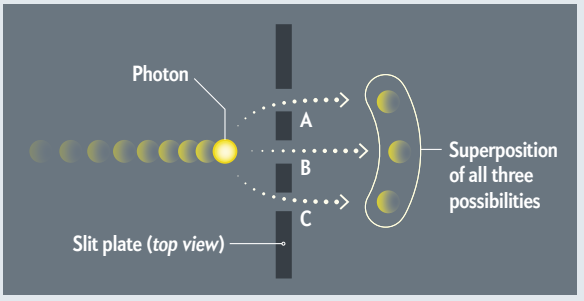
From Slits to Qutrits to Quantum Computing

Quantum computers promise faster computing than classical machines. Most quantum bits, called qubits, have two possible states (basis states), just as traditional bits do. But quantum bits with three or more basis states offer advantages.

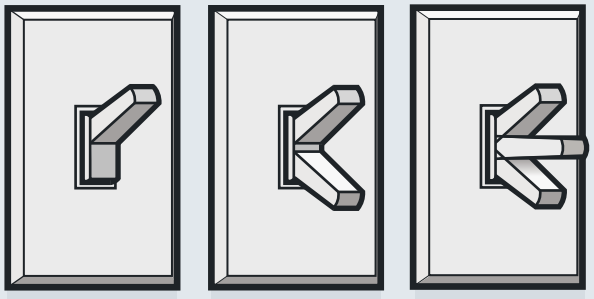
GENERATING A QUTRIT USING A SINGLE PHOTON

When a photon (a particle of light) travels toward the slits, it has an equal probability of going through each. A classical particle would pass through just one, but a quantum particle may actually go through all three, taking on a superposition state of being in three places at once. The photon can now be used as a "qutrit" with three basis states.



QUANTUM COMPUTING WITH QUTRITS

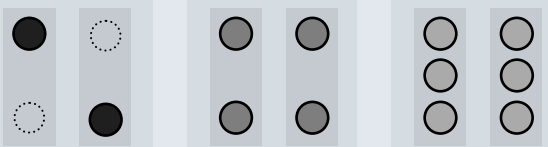
If scientists want to create a quantum computer with some total number of possible states, they would need fewer qutrits than two-dimensional qubits. This property is an advantage because the more bits in a quantum computer, the more likely it is to lose its quantum properties.



BIT
A classical computer bit has two basis states, like a light switch. It can be in only one or the other. With two bits, we can have four possible states.

QUBIT
A quantum bit also has two basis states, but it can be in both at once. The total number of states = 2^n, where n is the number of qubits. Two qubits gives $2^2 = 4$ states.

QUTRIT
A qutrit has three basis states and gives a total number of possible states = 3^n. For example, two qutrits gives $3^2 = 9$.



move to measure the different interference patterns as a function of detector position. We found that the interference pattern we measured did not match the approximate solution to the wave equation given by $\psi_A + \psi_B$, but it did match the solution that included the nonzero Sorkin parameter. We also used a blocking material to obtruct the space between the slits, essentially stopping the photons from traveling between the slits and interacting with the neighboring slits. When we did this, we saw that the value of the Sorkin parameter changed with the size of the block—showing that the parameter indeed measures interactions between the slits and that it varies depending on the level of interactions. This finding established that the correction term we measured was not some systematic error from our experiment that we had failed to understand but was indeed the thing we were looking for.

Ours was the first definitive validation of the Sorkin parameter as a correction term to the superposition principle in the classical microwave domain. The results, published in June 2018 in the *New Journal of Physics,* have already led to some textbook edits, and they affect our basic understanding of fundamental physics. They might also have implications for work being done in astronomy and astrophysics to study signals from the early universe. This research often involves arrays of radio antennas spread over the ground. Commonly, the data received by the different antennas are added together. But now that we know the wave-equation solution is not just the sum of the individual solutions, some calculations may need to be updated with the correct Sorkin parameter. Our findings might eventually help scientists develop better error models for these observations.

QUANTUM QUTRITS

OUR EXPERIMENT IS INTERESTING not only theoretically but also perhaps practically as well. We hope to use our triple-slit process to help design new tools for quantum computing.

Quantum computers take advantage of quantum laws such as superposition to enable computations much quicker than those of classical machines. Consider a traditional computer bit as if it were a light switch: it can be either "on" or "off" (corresponding to a value of 1 or 0, respectively, in binary code). In the quantum world, though, a switch need not be either on or off—it can be both. In a qubit, we define a state with a finite probability of being in the on state and in the off state at the same time. This combination of both states with some probability of each is the essence of superposition.

The two states that contribute to the superposition state are called the basis states. A regular qubit has two basis states, and for n qubits one has access to 2^n possible states. Thus, with two qubits, there are $2^2 = 4$ possible states. Whereas for n classical bits the state occurs in only one of the 2^n possibilities, for n quantum bits all 2^n possibilities can coexist. The power of quantum computing comes from cleverly designed quantum algorithms that can make use of the superposition state during execution and perform a certain class of operations at exponentially higher speeds than a classical computer.

Yet to reach this goal, we need a reasonably high number of qubits—certainly more than just two. One number many in the community are working toward right now is $n = 50$, which offers many interesting possibilities for quantum algorithms.

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With 50 qubits, we have 2^{50} possible states available for quantum operations. Recently Google claimed it had achieved this milestone by successfully implementing a random sampling calculation on a 54-qubit quantum processor. Getting to large numbers of qubits, however, is easier said than done. The more qubits we put together, the greater the chance they will lose their special quantum ability for superposition and collapse back into normal, classical bits. This happens when a qubit interacts with the outside environment and loses "coherence." As we try to get more qubits into a coherent superposition, it becomes more and more difficult to maintain this state for long. It is much like putting people into a room for a party. If you have 10 people in a 100-square-foot room, there is enough area for them to coexist without getting into one another's space. If we increase the number of people to 30, some crowding starts, which leads to a general loss of peaceful coexistence. The same thing happens with qubits.

One alternative to the usual strategy is to increase the dimension of each quantum bit rather than trying to fit more qubits into the same space. To see why this helps, let us go back to an elementary mathematics problem:

What is 2^3? The answer is, of course, 8 ($2 \times 2 \times 2 = 8$).

Now, what is 3^2? The answer here is 9 ($3 \times 3 = 9$).

These results are of the same order of magnitude—quite close. Thus, instead of three qubits, if we were to use two qutrits—that is, three-dimensional quantum bits—we would have access to a similar number of possible states. So, instead of trying to increase the exponent, why not try to change the base? If we increase the number of basis states, we will need a smaller number of bits to achieve the same goal. This realization is what defines research in higher-dimensional quantum systems.

And our strategy has another benefit: we are no longer bound by binary code. Consider the outcome of a game of football. Usually we think of two outcomes, "win" and "loss," which can be specified using two states, so in a quantum world a qubit is sufficient. But if we add two more possible outcomes, say, "abandoned" and "draw," one qubit is not enough to declare the results. We need two qubits. But if we had a four-state system, one would be enough. Such a system would be a "ququad."

Higher-dimensional quantum systems, or qudit systems, can thus pack more information in a smaller number of systems. This benefit has been theoretically proved to offer an advantage with respect to a certain goal for quantum computers—namely, creating hack-proof communication using so-called quantum key distribution. In this method, two parties create a shared secret "key" that only they can use to decode messages. If you can increase the dimension of your quantum bits by increasing the number of basis states, the result is a key that is more resistant to certain kinds of attacks. In addition to the possibility of higher security in key distribution, qudits also promise a greater amount of randomness in true random number generation—another hoped-for application of quantum computers.

Despite these benefits, qudit-based systems have some drawbacks. It is hard to actually come up with stable physical systems in which all the basis states are equally easy to reach. For instance, sometimes a system may be biased toward its lowest-energy, or ground, state, and resulting calculations could carry this bias. A second hurdle is simply that this line of research is newer than qubits, so fewer algorithms and tools have been developed for qudits. Although there is a lot to be done, the number of open problems makes this research exciting and rich in potential.

TOWARD A QUANTUM COMPUTER

SO HOW DO WE GET from our basic triple-slit experiment to a working qutrit system? The first step is to generate single photons.

We start with a very strong laser beam, which we shine toward a special crystal material. Under certain conditions, one in about 10^8 to 10^{10} photons splits into two photons of lower energy in a process called down conversion. The daughter photons always appear as a pair. We measure one of the photons using a single-photon detector, and this measurement heralds the presence of the other photon because we know they were produced simultaneously. We can then use the second photon for experiments.

In our team's work, we have played with the characteristics of the "mother" photon to ensure that the daughter photons share its characteristics. The mother photon is directed at three slits, and its spatial profile then mimics the triple-slit profile. The daughter photons in turn carry this profile through. The photon enters a superposition that gives us a "spatial-bin" qutrit whose three basis states are the three slit positions.

Still, this qutrit we have created is a far cry from what is needed for a functional quantum computer. We would need to use our slit system to generate numerous qutrits and then feed them into an architecture with so-called gate operations capable of using the qutrits to perform calculations. This area is the focus of my team's current efforts. We must design the specific optical elements needed to accomplish this manipulation and then miniaturize everything so it can define a working computer system.

Triple slits therefore represent the yin and the yang of physics research—both fundamental and functional. Our research on the superposition principle and its first measured correction term explores the very basic concepts of physics. Meanwhile triple-slit-based qudits represent a technological feat in the advancement toward higher-dimensional quantum computing and quantum communications. This most famous of physics experiments, it turns out, is still offering new insights and possibilities. SA

Urbasi Sinha is a physicist at the Raman Research Institute in Bangalore, India, as well as an affiliate member of the Institute for Quantum Computing at the University of Waterloo in Ontario and the Center for Quantum Information and Quantum Control at the University of Toronto. Her research focuses on experimental quantum information and quantum computing.

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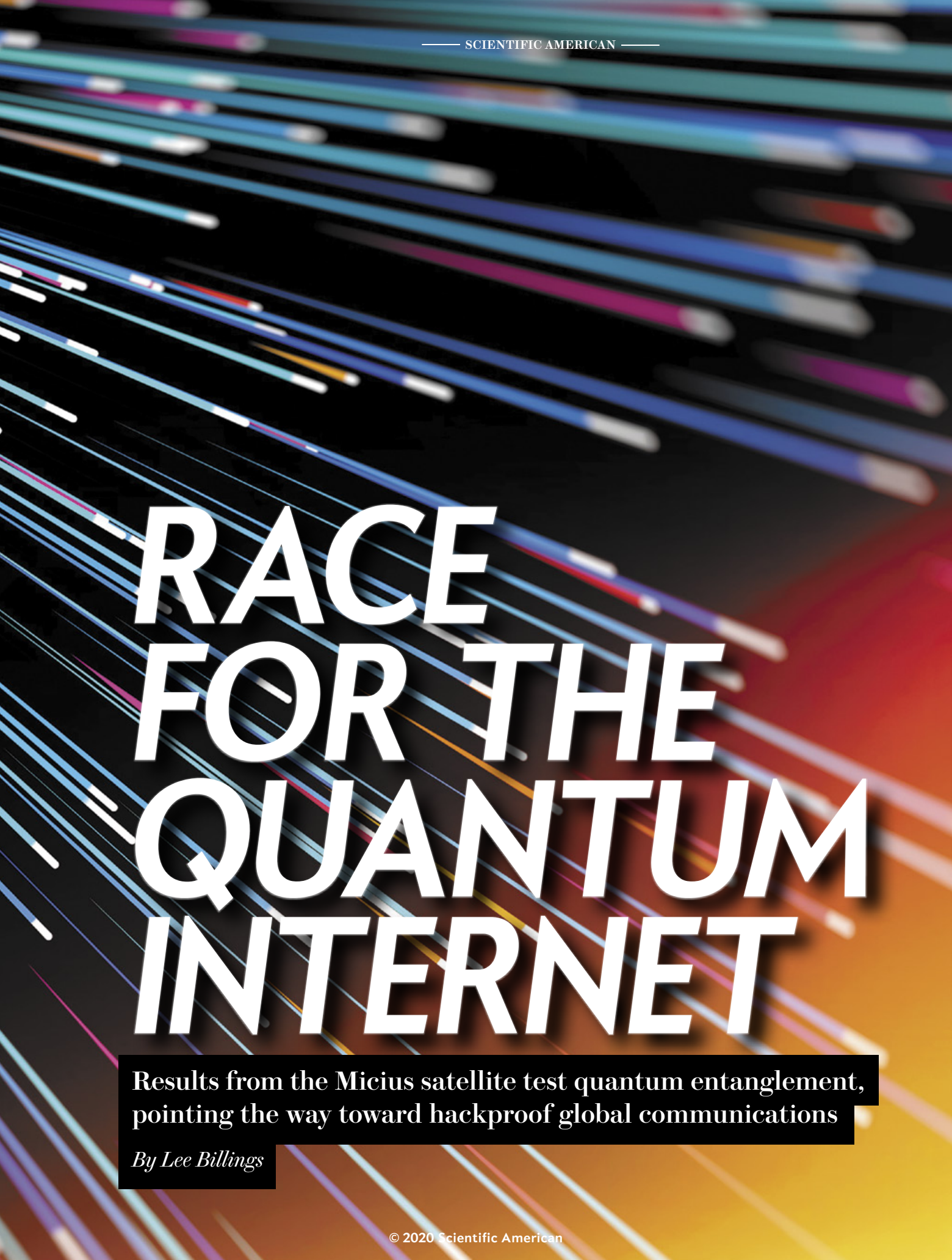

RACE FOR THE QUANTUM INTERNET

Results from the Micius satellite test quantum entanglement, pointing the way toward hackproof global communications

By Lee Billings

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IN A LANDMARK STUDY, A TEAM OF CHINESE SCIENTISTS USING AN experimental satellite has tested quantum entanglement over unprecedented distances, beaming entangled pairs of photons to three ground stations across China—each separated by more than 1,200 kilometers. The test verifies a mysterious and long-held tenet of quantum theory and firmly establishes China as the front-runner in a burgeoning "quantum space race" to create a secure, quantum-based global communications network—that is, a potentially unhackable "quantum Internet" that would be of immense geopolitical importance. The findings were published in 2017 in *Science*.

"China has taken the leadership in quantum communication," says Nicolas Gisin, a physicist at the University of Geneva, who was not involved in the study. "This demonstrates that global quantum communication is possible and will be achieved in the near future."

The concept of quantum communications is considered the gold standard for security, in part because any compromising surveillance leaves its imprint on the transmission. Conventional encrypted messages require secret keys to decrypt, but those keys are vulnerable to eavesdropping as they are sent out into the ether. In quantum communications, however, these keys can be encoded in various quantum states of entangled photons—such as their polarization—and these states will be unavoidably altered if a message is intercepted by eavesdroppers. Ground-based quantum communications typically send entangled photon pairs via fiber-optic cables or open air. But collisions with ordinary atoms along the way disrupt the photons' delicate quantum states, limiting transmission distances to a few hundred kilometers. Sophisticated devices called quantum repeaters—equipped with "quantum memory" modules—could in principle be daisy-chained together to receive, store and retransmit the quantum keys across longer distances, but this task is so complex and difficult that such systems remain largely theoretical.

"A quantum repeater has to receive photons from two different places, then store them in quantum memory, then interfere them directly with each other" before sending further signals along a network, says Paul Kwiat, a physicist at the University of Illinois at Urbana-Champaign, who is unaffiliated with the Chinese team. "But in order to do all that, you have to know you've stored them without actually measuring them." The situation, Kwiat says, is a bit like knowing what you have received in the mail without looking in your mailbox or opening the package inside. "You can shake the package—but that's difficult to do if what you're receiving is just photons. You want to make sure you've received them, but you don't want to absorb them. In principle, it's possible—no question—but it's very hard to do."

To form a globe-girdling secure quantum communications network, then, the only available solution is to beam quantum keys through the vacuum of space, then distribute them across tens to hundreds of kilometers using ground-based nodes. Launched into low Earth orbit in 2016 and named after an ancient Chinese philosopher, the 600-kilogram Micius satellite is China's premiere effort to do just that, as part of the nation's $100-million Quantum Experiments at Space Scale (QUESS) program.

Micius carries in its heart an assemblage of crystals and lasers that generates entangled photon pairs, then splits and transmits them on separate beams to ground stations in its line of sight on Earth. For the latest test, the three receiving stations were located in the cities of Delingha and Ürümqi—both on the Tibetan Plateau—as well as in the city of Lijiang in China's far southwest. At 1,203 kilometers, the geographical distance between Delingha and Lijiang is the record-setting stretch over which the entangled photon pairs were transmitted.

For now the system remains mostly a proof of concept because the current reported data transmission rate between Micius and its receiving stations is too low to sustain practical quantum communications. Of the roughly six million entangled pairs that Micius's crystalline core produced during each second of transmission, only about one pair per second reached the ground-based detectors after the beams weakened as they passed through Earth's atmosphere and each receiving station's light-gathering telescopes. Team leader Jian-Wei Pan—a physicist at the University of Science and Technology of China in Hefei who has pushed and planned for the experiment since 2003—compares the feat with detecting a single photon from a lone match struck by someone standing on the moon. Even so, he says, Micius's transmission of entangled photon pairs is "a trillion times more efficient than using the best telecommunication fibers.… We have done something that was absolutely impossible without the satellite." Soon, Pan says, QUESS will launch more practical quantum communications satellites.

Although Pan and his team later used Micius to distribute quantum keys between ground stations in China and Austria in 2017, enabling secure intercontinental communications, their initial demonstration instead aimed to achieve a simpler task: proving Albert Einstein wrong.

Einstein famously derided as "spooky action at a distance" one of the most bizarre elements of quantum theory—the way that measuring one member of an entangled pair of particles seems to instantaneously change the state of its counterpart, even if that counterpart particle is on the other side of the galaxy. This was abhorrent to Einstein because it suggests information might be transmitted between the particles faster than light, breaking the universal speed limit set by his theory of special relativity. Instead, he and others posited, perhaps the entangled particles somehow shared "hidden variables" that are inaccessible to experiment but would determine the particles' subsequent behavior when measured. In 1964 physicist John Bell devised a way to test Einstein's idea, calculating a limit that physicists could statistically measure for how much hidden

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variables could possibly correlate with the behavior of entangled particles. If experiments showed this limit to be exceeded, then Einstein's idea of hidden variables would be incorrect.

Ever since the 1970s "Bell tests" by physicists across ever larger swaths of spacetime have shown that Einstein was indeed mistaken and that entangled particles do in fact surpass Bell's strict limits. One definitive test occurred in the Netherlands in 2015, when a team at Delft University of Technology closed several potential "loopholes" that had plagued past experiments and offered slim but significant opportunities for the influence of hidden variables to slip through. That test, though, involved separating entangled particles by scarcely more than a kilometer. With Micius's transmission of entangled photons between widely separated ground stations, Pan's team has now performed a Bell test at distances 1,000 times greater. Just as before, their results confirm that Einstein was wrong. The quantum realm remains a spooky place—although no one yet understands why.

"Of course, no one who accepts quantum mechanics could possibly doubt that entanglement can be created over that distance—or over any distance—but it's still nice to see it made concrete," says Scott Aaronson, a physicist at the University of Texas at Austin. "Nothing we knew suggested this goal was unachievable. The significance of this news is not that it was unexpected or that it overturns anything previously believed but simply that it's a satisfying culmination of years of hard work."

That work largely began in the 1990s, when Pan, leader of the Chinese team, was a graduate student in the laboratory of physicist Anton Zeilinger when he was at the University of Innsbruck in Austria. Zeilinger was Pan's Ph.D. adviser, and they collaborated closely to test and further develop ideas for quantum communication. Pan returned to China to start his own lab in 2001, and Zeilinger started one as well at the Austrian Academy of Sciences in Vienna. For the next seven years they would compete fiercely to break records for transmitting entangled photon pairs across ever wider gaps, and in ever more extreme conditions, in ground-based experiments. All the while each man lobbied his respective nation's space agency to green-light a satellite that could be used to test the technique from space. But Zeilinger's proposals perished in a bureaucratic swamp at the European Space Agency, whereas Pan's were quickly embraced by the China National Space Administration. Ultimately Zeilinger chose to collaborate again with his old pupil rather than compete against him; today the Austrian Academy of Sciences is a crucial partner in the QUESS program.

"I am happy that the Micius works so well," Zeilinger says. "But one has to realize that it is a missed opportunity for Europe and others, too."

For years now other researchers and institutions have been scrambling to catch up, pushing governments for more funding for further experiments on the ground and in space—and many of them see Micius's success as the catalytic event they have been waiting for. "This is a major milestone because if we are ever to have a quantum Internet in the future, we will need to send entanglement over these sorts of long distances," says Thomas Jennewein, a physicist at the University of Waterloo in Ontario, who was not involved with the study. "This research is groundbreaking for all of us in the community—everyone can point to it and say, 'See, it does work!'"

Jennewein and his collaborators are pursuing a space-based approach from the ground up, partnering with the Canadian Space Agency to plan a smaller, simpler satellite that could eventually act as a "universal receiver" and redistribute entangled photons beamed up from ground stations. At the National University of Singapore, an international collaboration led by physicist Alexander Ling has already launched cheap shoe box–size CubeSats to create, study and perhaps even transmit photon pairs that are "correlated"—a situation just shy of full entanglement. And in the U.S., Kwiat is using NASA funding to develop a device that could someday test quantum communications using "hyperentanglement" (the simultaneous entanglement of photon pairs in multiple ways) onboard the International Space Station.

Perhaps most significantly, a team led by Gerd Leuchs and Christoph Marquardt of the Max Planck Institute for the Science of Light in Erlangen, Germany, is developing quantum communications protocols for commercially available laser systems already in space onboard the European Copernicus and SpaceDataHighway satellites. Using one of these systems, the team successfully encoded and sent simple quantum states to ground stations using photons beamed from a satellite in geostationary orbit, some 38,000 kilometers above Earth. This approach, Marquardt explains, does not rely on entanglement and is very different from that of QUESS—but it could, with minimal upgrades, nonetheless be used to distribute quantum keys for secure communications. Their results appear in *Optica*.

"Our purpose is really to find a shortcut into making things like quantum-key distribution with satellites economically viable and employable, pretty fast and soon," Marquardt says. "[Engineers] invested 20 years of hard work making these systems, so it's easier to upgrade them than to design everything from scratch.… It is a very good advantage if you can rely on something that is already qualified in space because space qualification is very complicated. It usually takes five to 10 years just to develop that."

Marquardt and others suspect, however, that this field could be much further advanced than has been publicly acknowledged, with developments possibly hidden behind veils of official secrecy in the U.S. and elsewhere. It may be that the era of quantum communication is already upon us. "Some colleague of mine made the joke that 'the silence of the U.S. is very loud,'" Marquardt says. "They had some very good groups concerning free-space satellites and quantum-key distribution at Los Alamos [National Laboratory] and other places, and suddenly they stopped publishing. So we always say there are two reasons that they stopped publishing: either it didn't work, or it worked really well!" SA

Lee Billings is a senior editor for space and physics at *Scientific American*.

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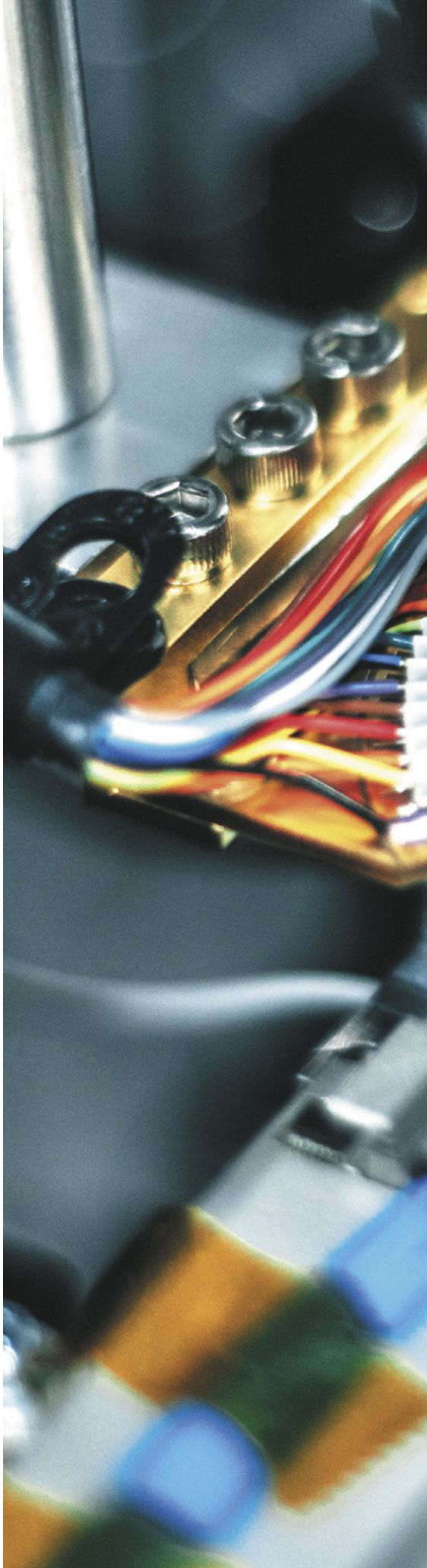
THE QUANTUM GOLD RUSH

The science is immature, and a multipurpose quantum computer doesn't yet exist. But that isn't stopping investors from pouring cash into quantum start-ups

By Elizabeth Gibney

ROBERT SCHOELKOPF SPENT more than 15 years studying the building blocks of quantum computers until, in 2015, he decided it was time to start constructing one. The physicist and his colleagues at Yale University began pitching their start-up firm Quantum Circuits to investors, hoping to persuade venture capitalists that the time was ripe to pour cash into a quantum-computing company. Within two years the team had secured $18 million. That was enough to build a specialist laboratory—which opened in January 2019—in a science park near the university in New Haven and to employ around 20 scientists and engineers.



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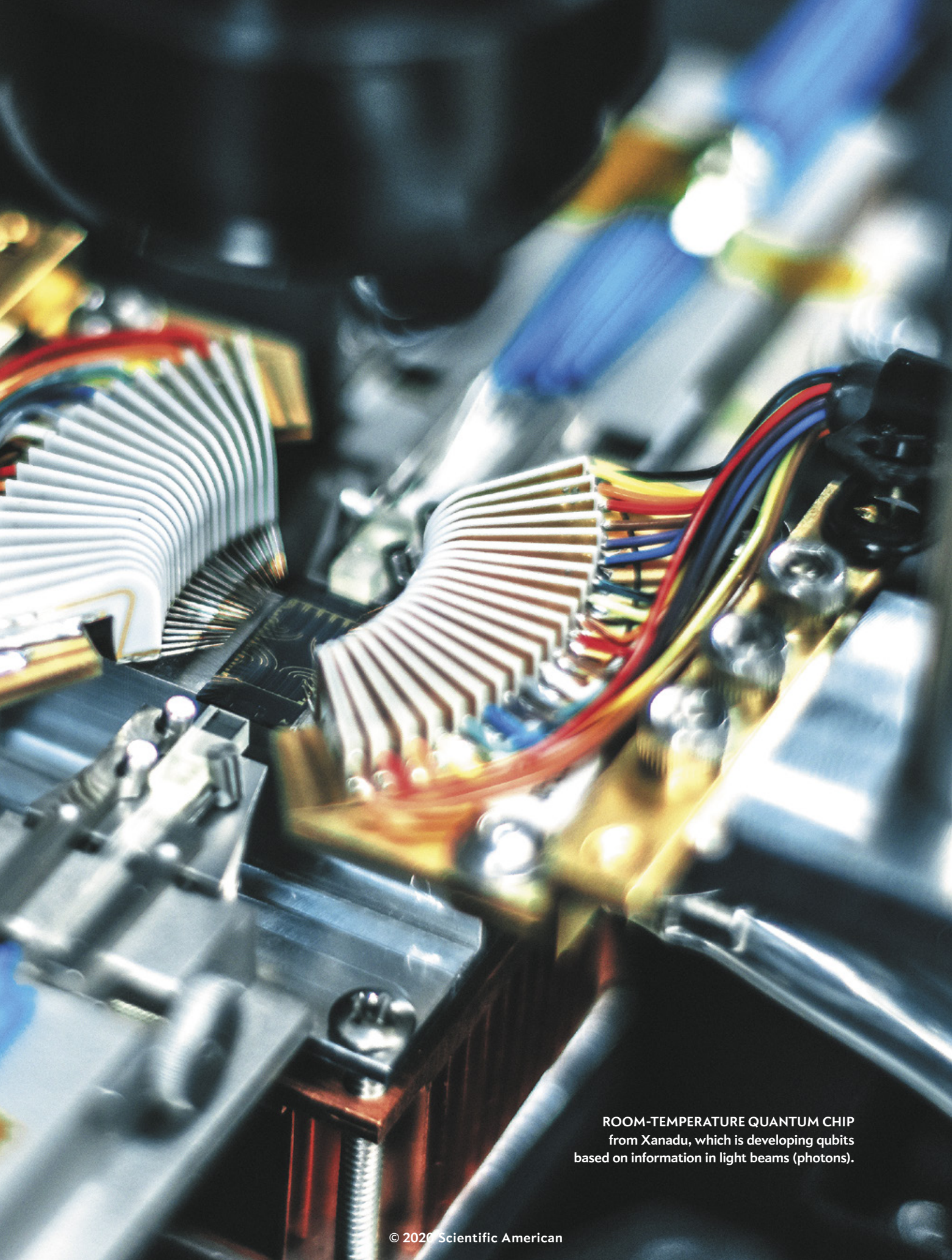

ROOM-TEMPERATURE QUANTUM CHIP from Xanadu, which is developing qubits based on information in light beams (photons).

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For Schoelkopf, venture capital (VC) investing was unfamiliar territory. But he's not the only quantum physicist to make a successful sales pitch. Governments and large technology firms have long nurtured quantum research and in the past few years have announced billions of dollars for the field. As their support has ramped up, outside investors have looked to get in early on a fledgling industry.

By the start of 2019, according to an analysis by *Nature,* private investors had funded at least 52 quantum-technology companies globally since 2012—many of them spin-outs from university departments. (Academics have founded many more start-ups that have yet to close deals.) Although the value of some of the cash infusions remains secret, *Nature*'s analysis captures the scale of recent activity. It finds that in 2017 and 2018, companies received at least $450 million in private funding—more than four times the $104 million disclosed during the preceding two years. VC makes up the bulk of this cash. Many firms in the VC hub of California's Silicon Valley have already plunged in, and among the rest, "most are keeping a close eye on quantum," says Christopher Monroe, a physicist at the University of Maryland, College Park, who co-founded in 2015 quantum-computing firm IonQ.

Few doubt that quantum technologies will eventually yield useful and potentially revolutionary products. Alongside government investments, hundreds of firms are rushing to invest in the field, with big names such as IBM, Google, Alibaba, Hewlett Packard, Tencent, Baidu and Huawei all doing their own research. Google has reportedly now created a quantum computer that can solve specialized problems that would stump even the best classical computer—a landmark known as quantum supremacy. Secure encryption using quantum technology is already a commercial product, as are some quantum-enabled technologies that sense, image or measure at exquisitely precise scales. Quantum-computing pioneer D-Wave Systems in Burnaby, B.C., even sells computers that exploit quantum effects, although these machines specialize in particular tasks known as optimization problems.

But venture capitalists tend to invest in what they hope will be game changers, such as a multipurpose quantum computer able to handle many kinds of otherwise unfeasible calculations. From the perspective of investors, the cash pumped into the field annually represents a small outlay so far—on a par with VC investments in artificial-intelligence firms before 2010, for instance. (By 2018 VC investments in the U.S. in AI had boomed to $9.3 billion.) Still, these numbers are substantial for an immature field that does not have much to sell. Despite the lack of progress, some software firms are already marketing their work on quantum algorithms, which are written for hardware that does not yet exist.

Many worry that the buzz could turn into a bubble. "There is a lot of hype right now," says Doug Finke, a computer scientist in Orange County, California, who runs the industry-tracking Web site Quantum Computing Report. Quantum technologies have seen rapid progress, yet machines that can tackle many kinds of computation are still likely to be decades away. Even then it will be difficult to write algorithms that harness their abilities, Finke says.

Some VC investors are betting on a breakthrough that brings general-purpose quantum computers to fruition in five or 10 years. Others are banking on making just enough progress for another firm to buy them out. Many also hope scientists can find applications for relatively small, imperfect quantum computers, which might emerge sooner. These would be limited to addressing specific questions, such as simulating a reaction in quantum chemistry or optimizing a financial model. They might not perform better than a classical computer that has unlimited computing resources, but they could still create marketable products.

If these early quantum computers do not emerge soon with profitable uses, the field could face a "valley of death" in which investment falters, warned a December 2018 report from the U.S. National Academies of Science, Engineering and Medicine. Some researchers worry about a "quantum winter" similar to the "AI winters" used to describe the lulls that followed surges of interest in that field. There are now hints that U.S. firms are finding it harder to get private funding, says Finke, who notes that seven out of 10 deals he has documented in 2019 were outside the country. "There is still a lot of value being created—it's just a case of whether there is too much hype," says Christian Weedbrook, founder of quantum-computing firm Xanadu based in Toronto.

IN BRIEF

Governments, technology firms and venture capitalists have pumped hundreds of millions of dollars into quantum technology. **Although they have experienced** massive progress, effective quantum computers are likely decades away. **The field of communication** is undergoing the most tangible growth—with quantum encryption perhaps proving to be the only secure way to transfer data.

CASH FOR QUBITS

QUANTUM TECHNOLOGIES have already transformed daily life. Computers, mobile phones, medical imaging, lasers and superconductors all emerged from the scientific revolution of the early 20th century, when physicists unlocked the inner workings of the atom through quantum mechanics. But today's generation of quantum technologies go further by manipulating previously untapped and often fragile quantum phenomena. These include superposition, in which particles seem to have multiple states until they are observed, and entanglement, which describes how the properties of quantum systems—such as particles' spin and polarization—can be inextricably tied together.

Such quantum technologies include unhackable encryption, supersensitive detection devices and new forms of imaging. The biggest game changer, if scientists can pull it off, would be a general-purpose quantum computer. By entangling collections of quantum bits, or "qubits," such a machine could perform calculations such as searching databases and

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factoring large numbers dramatically faster than the best classical computers can. "There is a whole class of problems that will always be impossible unless we have quantum computers," Monroe says.

To analyze commercial deals in the field, *Nature* cross-referenced details of quantum start-ups published on market-research Web sites and in consultancy reports, together with information provided by PitchBook, a market-research firm in Seattle.

Firms developing the physical qubits—the hardware of quantum computing—have received the lion's share of VC investment. Schoelkopf's company uses tiny loops of superconducting wire chilled to close to absolute zero for its qubits. This is the most intensively studied set-up for quantum-computing hardware: technology giants Google and IBM, for instance, use the same principles. (Internal research investments by big tech firms are likely to be large but are not publicly disclosed and so are not included in our analysis.) Google's biggest quantum computer has 72 qubits, but around one million will be needed for a general-purpose quantum computer. Monroe's firm uses another long-standing technology: applying magnetic fields to trap ions of ytterbium whose quantum state is read out using lasers.

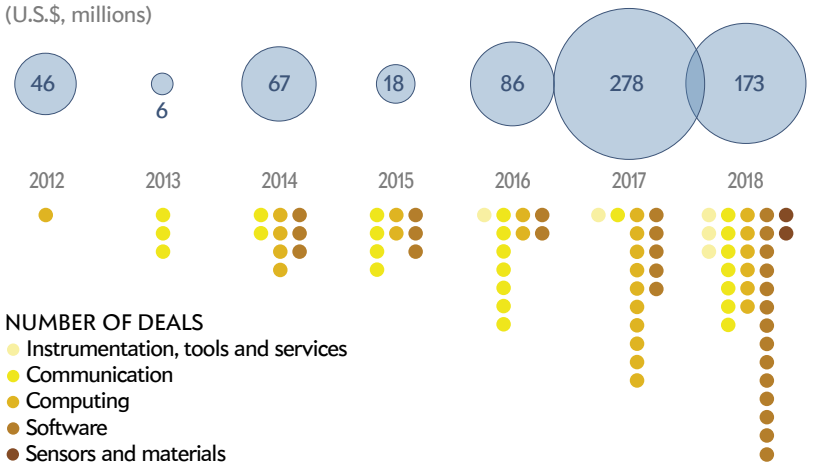
Other companies focus on different hardware that is at an earlier stage of development but that might prove easier to manufacture at scale. These are increasingly attracting investments, says Christophe Jurczak, founder and managing partner of Quantonation, a Paris-based venture fund that launched in 2018 and focuses on "deep physics" start-ups. Companies developing qubits based on light and on silicon have received VC investment on the scale of tens of millions of dollars since 2017.

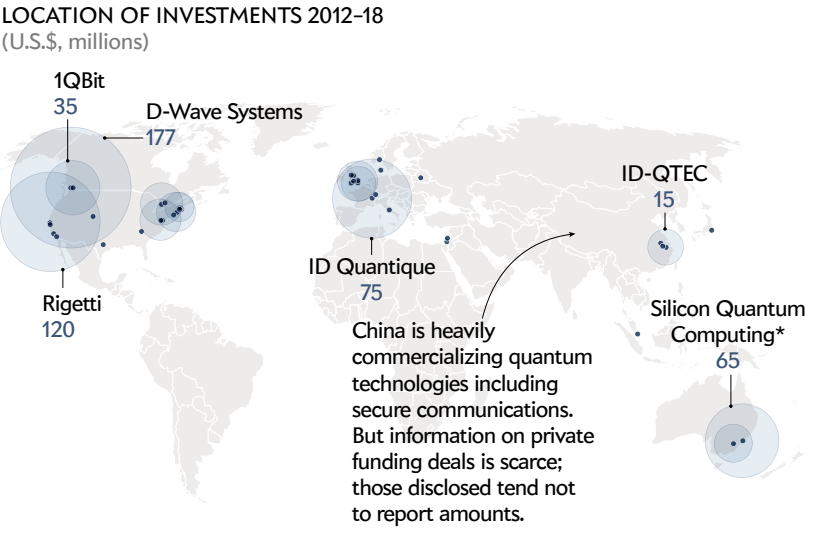
One firm—PsiQuantum in Palo Alto, Calif.—is promising to leapfrog its competitors to create a million-qubit computer in about eight years. Its unusual idea involves making qubits from photons of light guided through grooves etched into silicon chips. The advantage of this approach is that these qubits could be made in existing semiconductor manufacturing plants, says chief executive Jeremy O'Brien, who left his tenured position at the University of Bristol in England to co-found the firm in 2016. Although other academics remain skeptical about the company's claims, O'Brien says it is among the "top handful" of quantum companies in terms of investment and now employs a workforce of around 100. That might suggest it has raised dozens of millions of dollars, although the company won't publicly say so.

Quantum software is also proving a lure for private investment, with 20 firms raising more than $110 million across 28 deals from 2012 to the end of 2018. These companies are crafting algorithms that translate problems—such as optimizing the logistics of supply chains or simulating molecules for drug discovery—into software that could be run on early quantum computers. Money for software tends to come from "strategic" VC firms that are part of large corporations. These fund start-ups with the aim of

Investing in Qubits

A growing number of quantum-technology firms are raising cash from private investors, particularly in the sectors of quantum computing and quantum software.





*Includes unspecified contribution from the Australian government alongside private investors.

SOURCE: NATURE ANALYSIS, INCLUDING DATA FROM *QUANTUM COMPUTING REPORT*, BOSTON CONSULTING GROUP, PITCHBOOK AND CRUNCHBASE

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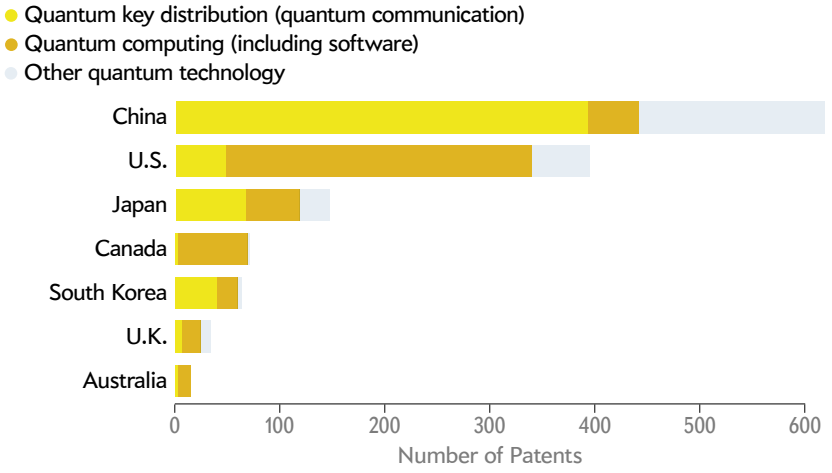
Quantum Patents

An analysis of global patents in quantum technology since 2012 shows China dominating quantum communication, but North America is ahead on quantum computing.



SOURCE: MARTINO TRAVAGLIN/EC JOINT RESEARCH CENTER

both developing the technology and making profits, says Matt Johnson, chief executive and co-founder of quantum-software firm QC Ware in Palo Alto, which raised $6.5 million in 2018. Purely profit-driven VCs aren't so interested yet, he says.

Several software start-ups have raised tens of millions of dollars each—including Zapata Computing in Cambridge, Mass., 1QBit in Vancouver and U.K.-based Cambridge Quantum Computing. Although no one is yet benefiting from quantum algorithms, some firms are willing to pay to develop them, says Yianni Gamvros, head of business development at QC Ware. That company has already signed contracts in industries such as aerospace, which plans decades ahead, and in finance, where tiny advantages can bring huge gains. The firm is developing algorithms that, on an early quantum computer, could solve those industries' biggest bottlenecks, he says. Many of the companies are still reeling from the impact of AI on their business. "This seems like a small investment to get ready for another potentially disruptive force," Gamvros says.

Computing isn't the only quantum technology attracting funds. Swiss start-up Qnami in Basel, which received $130,000 in 2018 to develop a quantum magnetic microscope using single electrons trapped in synthetic diamond, is one of at least three firms that have raised relatively small amounts of private cash to produce imaging or sensing technologies.

And it's hard to quantify the investments in one of the hottest quantum fields: communications, which uses entangled photons to create cryptographic keys that enable fundamentally secure data transmission. Thirteen firms that work on secure quantum communications have announced 27 deals that raised cash, but only around half disclosed amounts. The leaders in the field—Chinese firms QuantumCTek in Heifei City and Qasky in Wuhu City, both in the province of Anhui—have not revealed how much private funding they have received.

In Switzerland, ID Quantique in Geneva installed its first short-range system for the quantum encryption of ballot information in regional elections in 2007. Now Chinese engineers are taking quantum communications global: expanding on a 2,000-kilometer quantum link that was installed in 2014 and developing a network of quantum satellites after launching the first such craft in 2016. If quantum computers gain the ability to hack the best classical encryption, quantum encryption might prove the only route for secure communications.

QUANTUM GEOGRAPHY

NORTH AMERICA has long been the world's leader in attracting VC cash, and *Nature*'s analysis shows that the region also dominates private quantum investment. Yet the boom is not restricted to Silicon Valley. Firms in Canada have attracted $243 million, led by D-Wave Systems, which alone has raised $177 million. An entire ecosystem has emerged to support quantum companies around academic hubs in Waterloo and Toronto, which have benefited from public and philanthropic investment, tax advantages and successful incubators, Jurczak says. "You get very good vibes and connections there," he notes. A perceived immigration crackdown in the U.S. is also giving Canada an advantage in attracting talented quantum physicists, says Xanadu's Weedbrook. "We're seeing a reverse brain drain to Canada, and that's been great for us," he says.

The biggest gap in *Nature*'s analysis is caused by a lack of investment information from China. Reports in English-language media and by Western analytics firms rarely cover deals in China, which often involve state-backed VC firms, so our analysis is likely to miss a large number of contracts there. And in our data, only one in 10 fundraising deals secured by Chinese firms disclosed its value. Commercialization is well underway for many quantum technologies in China, says quantum physicist Jian-Wei Pan of the University of Science and Technology of China in Hefei; QuantumCTek was launched as a spin-out from his lab in 2009.

Patents offer another sign of the activity in China. More than 43 percent of quantum-technology innovations patented between 2012 and 2017 came from Chinese firms and universities, according to

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data gathered by the European Commission's Joint Research Center in Ispra, Italy. In patenting, China "has been extremely aggressive, especially in areas having to do with communication," says Celia Merzbacher, associate director of the Quantum Economic Development Consortium in Arlington, Va.

Elsewhere around the world, private funding mirrors research hotspots—with pockets of investment in Australia, Singapore, the U.K. and across Europe. European investors are typically more risk-averse and have smaller budgets, but a $1.1-billion flagship, launched by the European Union in 2018, aims to ensure that the region's strengths in basic research translate to commercial success. Through similar public-investment initiatives, the U.S., the U.K., Japan, Sweden, Singapore, Canada and China are all plowing hundreds of millions of dollars into quantum technologies.

QUANTUM BOTTLENECK

MOST UNIVERSITY SCIENTISTS who have founded start-ups, such as Schoelkopf, still spend time on campus, continuing research that could lead to further breakthroughs down the line. Only a few, such as PsiQuantum's O'Brien, have left academia entirely. Even so, the boom in quantum start-ups means that there are already too few highly qualified quantum engineers to supply the firms—and the industry, such as it is, risks draining academic talent away from universities, as happened in AI, Weedbrook notes. "I think we're starting to hit a point where we're concerned about it," he says. More training is needed: a major strand of the $1.2-billion National Quantum Initiative, which President Donald Trump signed in December 2018, is to train a new generation in quantum-related jobs.

At the same time, some firms are overpromising on the technology they can deliver, Monroe says. "There's a lot of hype in the field, a lot of promises that on the face of it look a little ridiculous, and some of that gets funded," he says.

Researchers wouldn't name particular efforts they felt were hyped, but Weedbrook pointed to the scale of investment in companies that focus only on quantum software as a sign of an investment bubble; some of them have raised tens of millions of dollars, even though they incur few costs for physical equipment or facilities. "There are amazing amounts being raised, so it seems to indicate that there is a lot of hype," says Weedbrook, whose firm develops both quantum hardware and software.

But quantum-software firms argue that their work needs cash for both intensive development and hiring staff. Companies must also cover their costs for longer than the two-year period that a typical funding round is expected to support, says Christopher Savoie, chief executive of Zapata Computing, which raised $21 million for quantum-software research earlier in 2019. This is because it remains uncertain when hardware for quantum software will emerge and because firms need funding to lure scientists away from stable academic positions, he says.

Not everyone is so concerned. O'Brien says that although VC firms might meet with researchers on the basis of buzz, he has not yet seen that translate into bad decisions. And even if quantum physics can seem counterintuitive, these technologies are not inherently harder to understand than many others, he notes. "There's some weird and wacky stuff going on, but there's weird and wacky stuff going on in a transistor."

If 2019 data end up showing that private U.S. investment in quantum technology is slowing down, Finke says, that might be because of fears of a quantum winter or the long time line to profitability for quantum firms. Increased competition among the large number of start-ups could also play a part, as well as concerns that the U.S.-China trade war might cool the economy, he adds. A hype cycle is mandatory for almost every high-tech market, says Merzbacher, who predicts that "breathless reporting and frothy announcements" are likely to die down. There are solid reasons to think that quantum technologies will create game-changing advances. "It's a question of the time line, rather than if that will happen," she says.

"THERE IS A WHOLE CLASS OF PROBLEMS THAT WILL ALWAYS BE IMPOSSIBLE UNLESS WE HAVE QUANTUM COMPUTERS."
—CHRISTOPHER MONROE
University of Maryland, College Park

Schoelkopf says that some firms are making grand promises on too short a time line. But he thinks that estimates on how long it will take to build a general-purpose quantum computer are overly pessimistic. "If you had projected forward from where we were 10 years ago, you would never have predicted how far we are today," he says. Innovative hardware combined with software that picks out the most tractable problems means "we're going to be reaching useful quantum computations faster than people think." SA

Elizabeth Gibney is a senior physics reporter for *Nature* magazine.

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Race for Quantum Supremacy Hits Theoretical Quagmire. Richard Haughton; Nature.com, November 14, 2017.

Beyond Quantum Supremacy: The Hunt for Useful Quantum Computers. Michael Brooks; Nature.com, October 2, 2019.

Quantum Computing: Progress and Prospects. National Academies of Sciences, Engineering and Medicine. National Academies Press, 2019.

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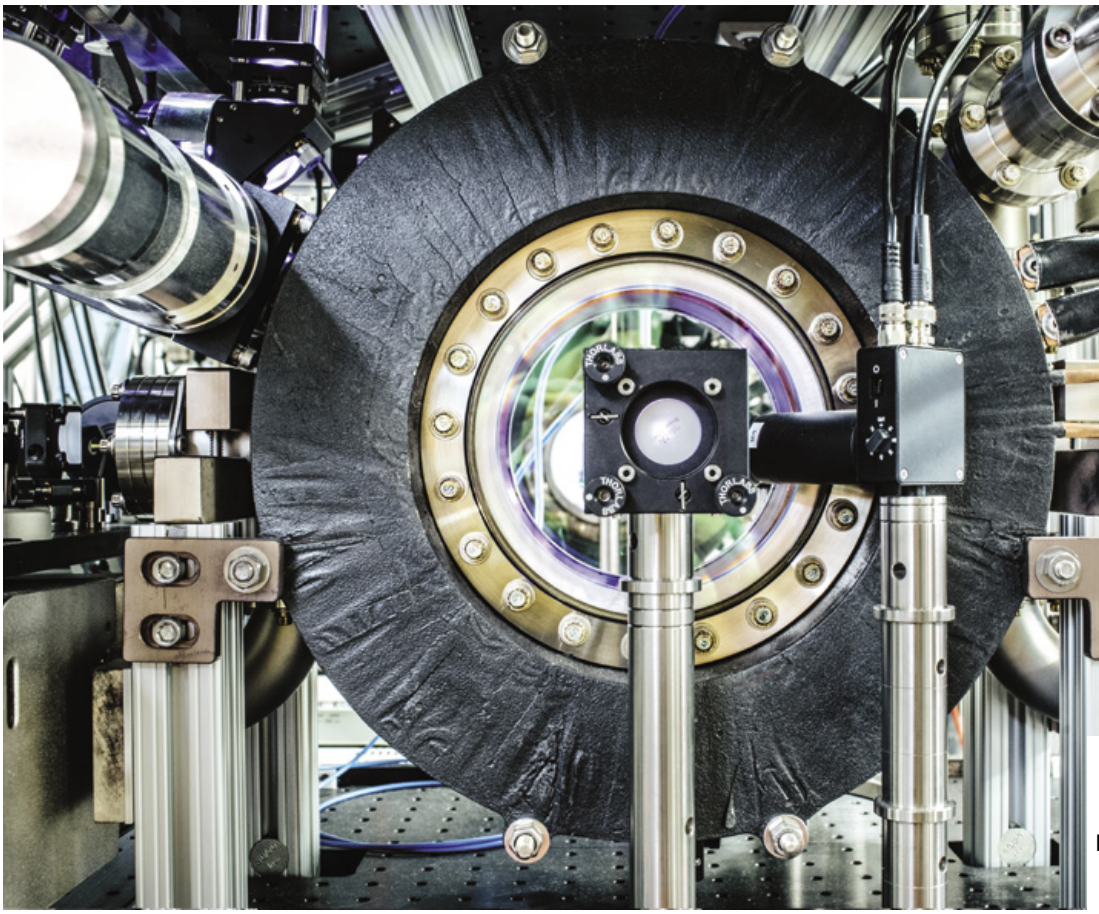

Close-up view of a vacuum chamber prototype to help levitate, trap and cool strontium atoms for the MAGIS project.

Giant Atoms

Room-sized "atom waves" could help probe the quantum realm

By Charlie Wood

Researchers are preparing to scrutinize nature on tiny scales by stretching supercooled atoms into room-length waves as they drop them down a 100-meter vacuum tube. The experiment will seek ripples in the bizarre quantum realm: potential fingerprints of missing dark matter and, in future iterations, new frequencies of gravitational waves.

Collaborators have raised $12.3 million to turn an Illinois mine shaft into the world's largest atom interferometer—the Matter-wave Atomic Gradiometer Interferometric Sensor, or MAGIS-100. The instrument will manipulate falling atoms with lasers. A laser pulse can tickle a single atom in such a way that, because of its quantum properties, it both absorbs and does not absorb the laser's energy. In terms of quantum mechanics, everything from a photon to a baseball has wavelike qualities—although they are imperceptible for large objects. When the MAGIS laser excites an atom, its wavelike nature lets it stretch out in space, the laser-absorbing part racing ahead.

After these atom waves, which measure several meters long, fall down the shaft, a second laser pulse will reunite the excited part of each wave with its slower counterpart. Researchers will then precisely determine the acceleration of the falling atom by measuring interference between the two parts of the wave. By simultaneously dropping a million such atom waves along the shaft's upper and lower sections, physicists will check more interference patterns—those between the top and bottom clouds of atoms—for minuscule contradictions to the known laws of physics. "The longer you watch [the atoms] fall, the more accurately you can measure them," says Stanford University physicist Jason Hogan, who has developed a 10-meter prototype.

Dark matter, which scientists suspect makes up much of the cosmos but which cannot be detected by conventional means, could cause noticeable effects in this experiment. Dark matter has many possible candidates, but ultralight particles—which Rob Plunkett, principal investigator at Fermilab, where MAGIS-100 will reside, calls "a whole unexplored continent"—are gaining prominence. If these phantasms meddle with MAGIS-100's atom waves, nudging them or tweaking fundamental constants, researchers just might catch the lightweights in the act.

And if dark matter remains dark to MAGIS-100, the apparatus doubles as a pathfinding gravitational-wave detector. It probably will not sense the subtle ripples in spacetime itself, but its technologies may enable a future kilometer-long "MAGIS-1000," which would be more sensitive to both gravitational waves and novel particles. SA

Charlie Wood is a journalist covering discoveries in the physical sciences both on and off the planet.

Photograph by Timothy Archibald

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